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editors

RELATING MACROSCOPIC PHENOMENA TO MICROSCOPIC PARTICLES

A central problem in secondary science education

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BIRD'S-EYE VIEW OF THE CENTRE

A.H. Verdonk
Chairman of the Centre for Science and Mathematics Education
University of Utrecht

Ladies and gentlemen,

It is my pleasure to welcome you to this Centre for Science and Mathematics Education of Utrecht University. I hope that this seminar organized by our Centre will be a stimulating and fruitful experience for all of us.

I consider it my task to inform you briefly about the activities of this centre, founded earlier in this year from four different departments of education.

The centre is staffed by about a hundred members: Mathematics: 40; Physics: 40; Chemistry: 10; Biology: 10.

These figures include scientific as well as service personel. Our activities include, roughly speaking, four areas: educational research (50%), development of curricula and teaching materials (30%) university education including teacher training (15%) and service activities (5%).

First of all I draw your attention to the educational research. The annual output of the centre includes about 70 scientific articles, 80 other articles and 5 theses. In 1989 and 1990 together perhaps even 18 theses will be completed. They are mainly related to secondary education (fig.1)

	Level of education		
Discipline	primary	secondary	university
Mathematics	2	0	-
Physics	-	6	-
Chemistry	-	3	3
Biology	-	1	-
Teacher training	-	3	-

Fig. 1 Distribution of theses among discipline and level of education in 1989 and 1990.

Mathematics (primary level) and chemistry (university level) have other levels of interest too. Research in the field of teacher training is carried out by the Centre in cooperation with the general institute for teacher training of Utrecht University. It focuses on university education itself as well as on teaching in the (secondary) classroom and it has a general character. Some of its topics are:

- interpersonal interaction of teachers;
- teaching behaviour in relation to professional satisfaction of teachers;
- cognitive growth of pupils.

The discipline-oriented research topics are mainly directed to concept development:
- realistic education in arithmetic and mechanics;
- energy and ionising radiation in physics;
- chemical element, equilibrium, measurement and synthesis, and calculations with chemical reactions in chemistry;
- homeostasis and health education in biology.

From an educational point of view we believe in learning by experience more than by transfer of knowledge and in education from real to realistic situations. We start concept development from pupils' own concepts and interests and we try to work not only within a context of explanations but especially of application and responsibility.

In our research we are seeking an educational structure of concepts using cycli of educational renewal.

Apart from research in concept development we also practise curriculum research. Some topics in this field are e.g. girls and physics and more generally the use of textbooks and the comparison of classroom climate in different countries.

Now we come to the second part of our activities: development of curricula and teaching materials.

In the field of curriculum development for mathematics I mention "The national program on arithmetic for the primary school", and for the secondary school "Mathematics 12-16" and "Requirements for mathematics examinations". We also cooperate in the national secondary education projects in physics, chemistry and biology for 16-18.

We develop teaching materials for secondary and sometimes for university education in science and mathematics, and for (in-service) education of teachers in science and mathematics.

From the teaching materials at a larger scale we mention the "PLON curriculum" for physics on the secondary level; "Chemistry in a Thousand Questions" for chemistry and a miscellaneous project on environmental education. Such activities mainly take place in cooperation with the Ministry of Education, the National Foundation for Curriculum Development (SLO) and occasionally with some other partners e.g. educational publishers.

For in-service training of teachers we have the following policy: the subject matter of the courses has to correspond with our other activities in educational research and development, unless there are new areas of interest on the national level. From a research point of view we try to apply our experimental teaching materials and collect research data in schools, from an educational point of view we try to promote the active participation of teachers in research projects.

In addition to educational research topics, which to a large extent return in in-service education, I mention courses about interactive video; use of micro-computers; molecules and atoms; thermodynamics; electrochemistry; spectrofotometry; pollution and safety; health in relation to genetics and to sports, stress and aids. Annual teacher meetings are also organized.

In the last part of this contribution I focus on educational activities in our own university and I will mention some additional service activities of the Centre.

We provide for teacher training before and after the masters degree. Further on we teach general and physical chemistry for the bachelors degree, environmental education and various specializations in educational research for the master's degree. All four groups of the Centre participate in the "Tijdschrift voor Didactiek van Wiskunde en Natuurwetenschappen" (Journal of Research in Mathematics and Science Education) and in an information centre for teachers. They also advise schools and companies.

The departments of education in mathematics and physics participate in designing curricula for developing countries. The mathematics department publishes a journal for teachers, the physics department provides a national schoolproject on ionizing radiation and also some industrial education. Finally the department of chemical education publishes a poster on chemical safety for schools and is engaged in developing studentcards in this field.

I thank you for your kind attention and wish you a fruitful seminar.

MACRO-MICRO: WHAT TO DISCUSS?
Opening speech

P.L. Lijnse
Centre for Science and Mathematics Education
University of Utrecht

1. INTRODUCTION

We are gathered here to mark the founding of the Centre for Science and Mathematics Education at the University of Utrecht. This Centre aims to coordinate and foster the work of four groups that up till now have been working separately in their respective fields of education. The Centre will concentrate its efforts on research into the learning and teaching of science. It is commonly recognised that research cannot progress without an intensive exchange of ideas and contacts. But, since Holland is a small country with very few people working in this field, we decided to invite delegates from other countries to attend this seminar. As this situation may not be peculiar to our country, we think it would be a good idea if this type of meeting could take place on a more regular basis. It would bring researchers in science education together in a kind of European college. I'ld like to discuss this idea with you during the seminar and we'll come back to it at the end.

2. CONCERNING THE TOPIC

We have organised this small-scale specific-topic oriented seminar as we think that in science education we are not yet at the stage of developing "grand unified" theories, but rather we are in need of domain-specific "local" theories. This is not to say that research into, for instance, general basic reasoning patterns or teaching strategies is not important, but in the end we always have to teach "something" and then the particulars of that "something" have to be taken into account.

This brings me to the topic of this seminar: "Relating Macroscopic Phenomena to Microscopic Particles: a central problem in secondary school science education". In deciding on this title, we may have been a little naïve, as we thought it would be clear to everyone what we had in mind. However, as one of the participants pointed out to us, shouldn't we have said sub-microscopic particles, or do we really mean microscopic, e.g. at the cell level? From the point of view of learning this difference is certainly not of minor importance. And what about macroscopic? Are we referring to phenomena on a human scale because of a possible relation with direct experiences, or are we also referring to phenomena on a supra-human scale such as those connected with ecosystems or cosmology?

In fact, we were thinking about relating phenomena, as we experience them "directly" in the world around us, to explanations in terms of some kind of particle model. One of the differences between physics/chemistry and biology is that in the former this transition is generally made in one step, whereas in the latter one can speak of a two-step process.

In discussing this topic, I see four interconnected problem areas which deserve attention, and which I will now describe briefly.

3. PHILOSOPHICAL-HISTORICAL REFLECTION

From this perspective we are faced with a number of questions of an epistemological and ontological nature. Some historical reflections concerning the genesis of concepts, theories and methods in science itself may help us to answer them. I'm referring now to questions like: What actually do we mean by the term phenomena? Can phenomena be perceived and/or experienced directly? What is the ontological status of a particle model? What is (are) the relation(s) between phenomena, empirical descriptions and theoretical models and explanations? When can we call an explanation scientific? How is scientific knowledge constructed and developed?

The answers to such questions are of direct importance for clarifying our aims and expectations in teaching the topic under consideration. Too often, I think, these kinds of questions are either neglected or the answers are taken for granted; this results in a distorted and simplified way of teaching.

4. EDUCATIONAL REFLECTION

Focusing on education we may well ask what particular aims and sequencing we have in mind when we introduce some kind of particle model in connection with phenomena. This question cannot be answered before we have described our general educational context. Do we teach about macro-micro to introduce pupils to the scientific structure and way of thinking for its own sake, or do we teach pupils from the perspective of relevance for everyday life situations? The approach that we adopt influences how we choose phenomena and the use we make of a particle explanation.

In a great deal of science teaching, a dominant perspective seems to be that it is only knowledge at the particle level which is considered to be real scientific knowledge. From a disciplinary scientific viewpoint, science is about explaining the world in a unified way and a particle model provides such a basic explanation. Therefore, particle models are often taught in some finalized form right from the start, as fundamental knowledge, without much phenomenological introduction and even without many explicit applications. These models are often assumed to function as explanatory models, almost as a matter of course. Such sequencing could be described briefly as "first and only particles". No wonder research shows this to be an educational misconception. It was not without good reason that the famous German physics educator Wagenschein a few years ago exclaimed: "Save the phenomena".

From the working papers I see that authors have adopted a variety of approaches; some authors see a particle model not so much as an aim in itself, but as a means of fostering "locally" a better understanding of phenomena (phase transformations, radioactivity) or of clarifying possible confusions between macroscopic concepts (internal energy and heat, voltage and current). Other authors seem to pay considerable attention to a phenomenological description in its own right, as a necessary foundation for a particle explanation given later. In other words: "phenomena first, particles later". Yet another way is not to introduce any kind of finalized explanatory model, either before or after the phenomena, but to develop macroscopic and particle descriptions of phenomena gradually in close connection, emphasizing a continuing process of "back-and-forth" thinking between both levels.

In conclusion I would say that we have apparently no uniform opinion about the aims and sequencing when we speak about macro-micro relations. They can be approached from a number of different perspectives. So, this seems to be a second point that needs further clarification.

5. THE TEACHING/LEARNING PERSPECTIVE

a. Two domains?

We all know about the problem of pupils' conceptions regarding particle interpretations and model making. Less attention is paid to pupils' descriptions of phenomena, though this could be of equal importance. A general problem for pupils may be that they are assumed to learn to think in terms of a model which they cannot see, for which they may feel no apparent need, and which is constructed by someone else in order to explain experiences and phenomena that for them may not require an explanation at all. Or to put it differently, the distance between lifeworld thinking and scientific thinking may be greatest for this topic. We need to analyse this distance further by mapping out lifeworld and scientific ways of reasoning concerning phenomena and particle models, as well as by looking for common patterns or "phenomenological primitives" that may be useful in bridging the possible gap.

b. Views on teaching/learning

Before domain-specific theories concerning the teaching and learning of particle models can be constructed, we also need to opt first for a certain view on the teaching/learning process. Do we regard "direct instruction aimed at transfer of knowledge" as an acceptable (and possible) way of teaching/learning, or do we need a "constructivist view, aimed at the development of knowledge"? From the working papers, I get the impression that most people present could agree on a constructivist view of learning, though I'm not sure that everybody understands this in the same way. Starting from intuitive ideas does not necessarily mean constructivist teaching. Anyway, constructivism, whatever it may mean, is still not a theory; it is only a possible starting point that should have consequences for teaching; further discussion and research are needed.

One may ask, for instance, in what way is a constructivist view related to a certain preferred conceptual sequencing. Or, to put it differently, can a constructivist view be joined unproblematically to a traditional conceptual teaching structure that is directed towards the early introduction of a particle model, or does such a view by its very nature require a more phenomenological approach?

c. Levels in concept development

An interesting additional viewpoint, expressed in several working papers, is the attempt to distinguish concept levels in the teaching sequence in order to gradually bridge the gap between the lifeworld of pupils and science. A possible level description reads as follows.

We start at the lifeworld level, which is meant to reflect both in its content and its pragmatic perspective the characteristics of lifeworld thinking and reasoning. Starting from this level, in teaching one first has to make a selection of phenomena in a way that is clear and meaningful for pupils. Characteristics of these phenomena, and relations between them, can be investigated and described in the first instance at a qualitative level. A possible following step is to make these concepts and relations quantitative. Though both levels may profit from and be closely related to "direct" experiences and measurements, and are therefore usually described as empirical, from a philosophical and learning point of view we are already dealing with theoretical constructs and concepts, that require the development of a certain "non lifeworld" perspective.

A subsequent step, which may also follow the qualitative level, is taken when we make the transition to the "explanatory" particle level. This transition requires a new motivation which should derive from a need that is experienced as such at the lower level. Commonly, the relation between lifeworld thinking and science, if at all, is described as though it involves one big step.

This level scheme emphasizes that this step can be broken up into several smaller steps. It may be important to note that at each level we are dealing with a network of "actional" concepts and relations, which needs to be developed as such before a meaningful transition can be made to the next level. Such a transition requires reflection on the characteristics of the lower level network, and motivation to make this transition. One may wonder what these levels look like and how large the gaps are between them. No general answer can be given to these questions since both aspects are probably contentspecific. From the point of view of learning, the problem is how continuous or discontinuous the transitions are or can be made in a teaching/learning process. What measures can be taken to let pupils make these transitions and at what level should the teaching process start and end? If these levels can be considered as hierarchical, and if at least some of the transitions are discontinuous, does a constructivist view of learning then not automatically mean that the teaching process should be structured accordingly? And does this also mean that a direct transfer of knowledge is doomed to failure?

lifeworld reasoning
macro phenomena (contexts)
macro qualitative reasoning
macro quantitative reasoning
micro particle level

In my view, if we succeed to describe the levels and their differences, and we can identify ways of letting pupils make the transitions, we will have taken an important step forward towards a domain-specific theory (or theories) in connection with the topic under consideration. This theory of course needs to be developed as a direct result of empirical research in classrooms, for which action research could be an essential research paradigm.

The papers delivered at this seminar, contain many contributions on this subject though the synthesis has not yet been made. To achieve such a syntheses, one has to relate, discuss and work out in a coherent way ideas about conceptual change, the role of pupils' own constructions and motivations, the role of phenomenologies and phenomenological primitives, the role of cognitive conflicts and reasoning patterns. Other aspects important for such a synthesis are analogies, experiments and experiences, metacognition and reflection, as well as the perspective of social constructions, language formation and communication, to mention only a few of the aspects that are dealt with in both the working papers and current research literature.

6. WHAT RESEARCH DO WE NEED?

Implicit in the above is a research agenda for the future. Internationally, in my opinion, research efforts in science education are rather scattered and diversified. It is difficult to speak of a productive research programme in the sense of Lakatos. As a result little progress is being made at an applicable level. Theory development, if there is any, seems to take place mainly at a too general psychological level. Many piecemeal results are reported, but it is very difficult to say that the whole is much more than the sum of its parts. This criticism applies particularly to much of the American research. It's my impression that in Europe we are working more from similar perspectives, even though our work is not organized in a particular way.

If it is true that "applicable" progress should also be made at the level of subject-specific theories, I wonder whether we could not arrive at some kind of coordination and cooperation at that level. This could mean choosing some key topics, e.g. structure of matter, chemical substance and reaction, genetics, to mention one item from each of the sciences represented here. It is important to choose a theoretical framework as a starting point, and to obtain agreement about research questions and methodology, so that people may work on pieces of a puzzle that will eventually fit together. I realize that such coordination cannot come into being at one seminar. Probably many discussions and meetings will have to take place before such a common research programme can be formulated and put into practice. It would be good if this seminar were to be a first step in that direction. It would be even better if we could agree on the need for another seminar in the near future.

PUPILS' CONCEPTIONS OF MATTER AND ITS TRANSFORMATIONS (AGE 12-16)

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University of Göteborg

1. INTRODUCTION

How can pupils' thinking about matter be characterized?

A common method of finding out how pupils think is to give them various assignments either in the form of interview questions or paper and pencil problems. Besides solving the problems, they have to explain how they worked them out. The pupils' answers as such often make interesting reading, but if one merely describes these, one is soon swamped in detail. This is why attempts are made to sort the answers into categories, which may be based on one or more problems. Sometimes a general description is also formulated concerning everyday thinking in a certain area. One can, in other words, speak of four levels of description, namely, the pupils' answers as such (I), categories based on one problem (II) or more (III) and a general description (IV). The different levels are complementary. What one gains in generality, one loses in concreteness and fine detail. This means that all levels of description are needed.

A fair number of studies have been devoted to the area of matter, for example, how pupils explain chemical reactions and how they understand the structure of matter. Some of these contain relatively few references to other work. The reports tend to concentrate on descriptions at levels I and II. One can therefore say that there is a need, firstly, to collect together and structure these studies in order to stimulate communication among researchers, secondly, to find more general characteristics of everyday thinking, that is, descriptions at levels III and IV. This article is an attempt to achieve this. It is a question of discovering the essence of pupils' everyday thinking so that efforts to improve teaching are directed along the right lines.

Clues as to what form a general description can take may be obtained from Pfundt (1981) and Nussbaum (1985). They point out that a large percentage of the pupils' answers indicate that, in everyday thinking, matter is conceived as continuous and static. There is no vacuum. Matter can, to be sure, be divided up into, for instance, grains and drops, but these particles are also seen as continuous and static. The dynamic picture of atoms and molecules in never ending motion and interaction in empty space is not accessible to the everyday observer.

When taking Pfundt's and Nussbaum's observations as level IV description, we obtain a common element in the presentation of various research results, but the significance of this should not be exaggerated. It is the combined knowledge from all the levels of description that is of most value to teaching. Nor should the idea of the continuum be regarded as incorrect, but as a model of matter. In the mechanics of materials, for instance, it is assumed that matter is continuous.

We shall begin with a description of pupils' everyday thinking about matter - how they explain the phenomena known to the scientist as chemical reactions and changes of state, how they solve conservation problems and how they conceive states, particularly the gaseous one. Then follows a description of what happens when the pupils take their first steps into the world of atoms and molecules. After that, specific educational implications of the research findings will be discussed leading up to a critical examination of current teaching practice.

2. EVERYDAY UNDERSTANDING OF MATTER AND ITS TRANSFORMATIONS

2.1 Chemical reactions

Pupils' thinking about chemical reactions has been studied by Andersson and Renström (1981, 1983a, 1983b), Pfundt (1982), Shollum (1982), Andersson (1984, 1986), Méheut, Saltiel and Tiberghien (1985) and De Vos and Verdonk (1985a, b, 1986, 1987a, b). Five categories of answers, or transformation models, can be distinguished in the large amount of material collected, namely, disappearance (A), displacement (B), modification (C), transmutation (D) and chemical interaction (E). Characteristic of A, B, C and D is that the pupils imagine that a new substance appears, and an old one disappears, as a result of a separate change in the original substance, or possibly changes, each one separate, in several original substances. The original substance can in itself interact with another substance, but it does not form a new substance with it. This scheme of categories is a development of those suggested by Pfundt (1982), Shollum (1982) and Méheut et al. (1985). See Andersson (1986) for a comparison of the various suggestions.

A. Disappearance

Andersson and Renström (1983b) have given the "Exhaust" problem, invented by Renström, to 2800 pupils in forms 7-9: "A car weighs 1000 kg. It is filled up with 50 kg of petrol. The car is driven until the petrol tank is empty. The car then weighs 1000 kg again. Approximately how much do you think the exhaust gases given off during the drive weigh? Explain your reasoning." About 15% of the pupils answer as follows: "The petrol is used up in the car and disappears. Only a small part of the petrol turns into exhaust".

B. Displacement

A substance can appear in a given place simply because it has been displaced. (Displacement is a concept from physics which means 'change of position'). The substance as such does not change, for instance, the drops on the water but have seeped through the sides. The pupils use this idea to explain what the scientist would call chemical reactions. Meheut et al. (1985) have interviewed 12-year-old pupils about the combustion of alcohol and wood. The investigator and each pupil carry out the combustion experiment together. A product of combustion, water, becomes visible thanks to condensation. Fred, one of the pupils, uses the displacement concept in answer to -Tell me what happens! "Water vapour ... there isn't any water in alcohol. I don't see what the water vapour is doing here". According to him, a certain combustion product must have existed from the start in order to be separated out when the substance burns.

De Vos and Verdonk (1985a) have asked pupils, 14-15 years of age, to mix lead nitrate and potassium iodide in a mortar with the help of a pestle. A yellow colour appears immediately (lead iodide). Very frequently the pupils explain the yellow colour by saying that the white grains are like eggs. If they are crushed with a pestle, then the yolk comes out and colours the mixture. The authors point out: *It seems that most children at the age of 14 still firmly adhere to an unspoken and unconscious idea, that each individual substance is conserved, whatever happens to it.*

C. Modification

Modification implies that a substance retains its identity while some of its properties are changed, for instance the ice in the ice-cube rack is not a new substance, but frozen water. The pupils use this idea to explain chemical reactions. One of the pupils that Mheut et al. (1985) interviewed says: "When you burn the alcohol, there's alcohol vapour. When you heat water in a pan there's water vapour. As the alcohol burns, the alcohol turns into alcohol vapour, you can see it, we did the experiment where you hold a glass on top, and when you lifted it off it smelt of alcohol".

D. Transmutation

This category comprises a number of transformations that are "forbidden" in chemistry.

A given substance is transmuted (partly) to energy.

Concerning the "Exhaust" problem mentioned above 3 per cent of the pupils answered as follows: "Less than 50 kg. It's less than 50 kg because part of the petrol has been changed into heat and kinetic energy".

Energy is transmuted into a substance.

Examples of this idea are to be found in Meheut et al (1985). One pupil who is required to explain why water is formed during the combustion of, for instance, a candle or alcohol says: "You can see little drops of water because the flame heats, and the heat goes off as steam and after that it turns into water".

A given substance is transmuted into a new substance.
Andersson and Renström (1981) have asked 590 pupils in forms 6-9 to explain what is known as the iron wool experiment. A wad of iron wool is balanced in a scale, set alight and allowed to burn. Then the pan with the wad sinks down slowly. The wool, shiny like metal to begin with, turns dark. About 10% of the pupils explain this as follows: "The iron wool that has burnt has turned into carbon. Carbon weighs more".

E. Chemical interaction
The studies performed by Andersson and Renström (1981, 1983a, 1983b) show that relatively few pupils answer the test questions in a way that is chemically acceptable. The problem about iron wool was answered satisfactorily by about 15% of the pupils after instruction. The exhaust problem is solved by only 2% after instruction: "The petrol combines with oxygen. Then the exhaust gases weigh more". Similar results have been obtained by the English national assessment program "APU Science Project". See e.g. Donelly and Welford (1988).

Comments
Let us now try to link up the pupils' explanations of chemical reactions with the general description of everyday thinking about matter that was suggested in the introduction. We can then conclude that the conception of matter as continuous and static does not leave room for the idea that two substances in contact can react with each other so that the original substances disappear and new ones are formed. The original substances simply exist - in contact, to be sure, but each one separately. To explain changes that actually do occur, the pupils are forced to use models that imply that each of the substances is changed under the influence of external agents. Disappearance, displacement, modification and transmutation are models of this kind. One can therefore say that the way in which the pupils explain chemical reactions is, at any rate, "compatible" with the statement that matter in everyday thinking is understood as continuous and static.

2.2 Changes of state
Most studies mentioned in the previous section were conducted in order to explore pupils' thinking without any definite hypotheses concerning its nature. In the description of the results, the emphasis is laid on categories that are connected with specific problems. 'Disappearance', 'displacement', etc. are suggestions for categories that are common to many problems. These more general categories can, however, only be based on a part of the pupils' responses, for the simple reason that many of them are impossible to interpret because of the ambiguity of the language. If one pupil, for example, writes "an oxide is formed" to explain why a copper pipe turns black, one does not know whether this indicates an understanding of chemical interaction or is a pure description, or whether the pupil imagines that some substance in the air forms a coating.

With reference to pupils' ideas about changes of state, studies have been reported by Osborne and Cosgrove (1983) and Bar (1987, 1989). It turns out that the transformation models from the section about chemical reactions can be used to structure the students' answers, even if the difficulties of interpretation just mentioned do exist.

A. Disappearance

Bar (1987) has, among other things, interviewed Israeli children, aged 5-11, about the following problem: "Water was spilled on the floor. After some time the floor was dry. What happened to the water? Where can it be found?" 60% of the five-year-olds answered that the water had disappeared. The popularity of this view drops quickly between 6 and 7 years.

B. Displacement

Somewhat older children in Bar's study answered that the water penetrates the floor. This displacement view peaks between seven and eight years (65%). Bar explains her answers with reference to results of some piagetian tests given to the interviewed children. She finds that students with the disappearance view do not conserve amount of liquid. Therefore, there is nothing in their reasoning that forbids matter to disappear. Students expressing the displacement view, on the other hand, do conserve amount of liquid, but do not conceive air as something permanent, that is, they have not constructed the idea that matter may exist in an unseen form. Therefore, the idea of evaporation is not within their reach. They express a view that is in line with their conservation reasoning.

The study reported by Osborne & Cosgrove contains both interviews and written tests with pupils aged 8-17 years in New Zealand and deals with the transitions between ice, water and steam. One of the test problems concerned boiling water, which the pupils interviewed - 43 of them - first observed and described. They were then asked "What do the bubbles consist of?", followed by "How are the bubbles formed?" Some of the pupils are of the opinion that the bubbles contain air, which comes from outside, for example: "...When the water comes up to the surface, it cools and will go down again and might have sort of trapped some air in it".

C. Modification

When, besides being able to conserve amount of liquid, the children interviewed by Bar conceive air as something existing permanently, they explain the disappearance of water by saying that it changes into vapour, that is, small unseen paticles. Water is modified into water vapour. The popularity of this view increases with age, reaching 60% at twelve.

D. Transmutation

In the study by Osborne and Cosgrove about boiling water, it was quite common for interviewed students to say that the bubbles contained air.

The most common explanation for this was that water is transformed into air, for instance: "The heat of the element could turn some of the water into air." This answer might be interpreted as indicating a transmutation idea. (The word air might also refer to an undifferentiated idea of something gaseous.)

E. Chemical interaction

A chemical model is sometimes used to explain phase change: "The atoms of oxygen and hydrogen are rising up from the water". Separately? "Yes, separately, and when they hit something they sort of join together and form little drops of water". (Osborne & Cosgrove, 1983).

In the New Zealand study, a larger group of pupils were given the following written problem: "When a jug boils there are large bubbles in the water. What are the bubbles made of?" The pupils were confronted with four alternatives. In the age-group 12-15 years, just over 10% chose "steam", 20% "heat", just over 30% "oxygen or hydrogen", and the same percentage "air". In comparison with this water-steam transition in boiling-bubbles, the pupils give considerably better answers about the transition ice-water. Nearly all the subjects in the New Zealand study stated, for example, that water is formed when ice melts. This should not, however, be interpreted as a sign of a general phase concept. Karplus (1966) has reported that if you melt a salt (phenylsalicylate), causing it to be transformed into a clear liquid, both primary school pupils and college students on the Arts side say that water is formed. It is, however, not clear what the students mean by water. One interpretation is that they see a similarity between ice that melts and mean the substance water. In other words, it is a question of a transmutation. Another interpretation is that when the students say water they mean liquid. To them water is a prototype liquid, but they only have the word water with which to express their understanding. Yet another possibility is that the students imagine that water is present in all liquids as a kind of bearer of the principle of wetness. Differences between liquids can be explained by the admixture of yet another substance, which varies from liquid to liquid. Stavy and Stachel (1985a) have attempted to clarify this problem. They claim to have empirical evidence that quite a number of pupils aged 5-12 years believe that a solid substance - candle wax - is transformed into water when melted. The issue is complex, however, making further investigations desirable.

Comments

In the responses just reported regarding changes of state, we can see the same pattern as for chemical reactions. A large proportion of the pupils use models "compatible" with the conception that matter is continuous and static, namely disappearance, displacement, modification and transmutation. The test problems can, in principle, be solved with the modification model. Water is modified, for example, into steam, which exists in the boiling bubbles. But the older pupils who answered correctly during the interview tended to express the dynamic particulate conception of science when they explained how they had reasoned. The details in the answers to the test problem are probably determined by how a given test problem interacts with the pupils' experiences within the framework of the conception that matter is continuous and static. Associations and the formation of analogies would appear to play a part. When the pupil sees condensation on the sides of the tin containing ice, he perhaps thinks of containers that leak, such as a water butt or a cracked coffee cup, and draws a parallel. Another thinks of a cold, damp cellar and believes that coldness and dampness are synonymous, or that coldness creates, or is transformed into, dampness.

2.3 Conservation

Conservation of amount of matter

Pupils' understanding of conservation of amount of substance during transformations, including changes in temperature, pressure and state as well as chemical reactions, has been investigated by Dow, Auld and Wilson (1978), DES (1982), Andersson (1984), Driver (1985), Séré (1985), Stavy and Stachel (1985a), Mas, Perez and Harris (1987). (Amount of matter refers to a more intuitive concept than mass, the meaning of which is provided by Newton's laws.)

Let us look at a typical test problem and the students' answers (DES, 1982, p.119, Andersson, 1984.)."A piece of phosphorus was placed in a flask as shown in the figure. (The figure shows a sun, a magnifying glass and a flask with a piece of phosphorus in water and an airtight stopper.) The flask and its contents weighed 205 g. The phosphorus was then set alight with the help of a magnifying glass. It burned for a little while. Then white smoke was formed, which slowly dissolved in the water. After cooling, the flask with its contents was weighed again. What does it weigh now? More than 205g, 205 g or less than 205 g. Explain how you thought this out!"

The students' answers are influenced by their conceptions of how matter is transformed:
Disappearance: "The weight burns up. As the flask was corked, nothing could disappear. But as the oxygen had been used up because a substance had burnt in the glass, the weight was less".
Displacement: "The smoke was already there in the tablet, although it weighs more in compressed form".
Modification: "When the phosphorus burned, the phosphorus was only transformed into another form. The weight is the same".
Transmutation: "Less than 205 g, because the energy (heat) caused by the fire disappears when the flask cools down".

The students' answers are also influenced by their conceptions of weight: "Smoke doesn't weigh anything". "A gas is formed so that the flask is lifted". "Gas is lighter than a solid".

In the study reported by Andersson (1984), only 26% of the students in form 9 (16 years of age) answer 205 g and give a correct conservation argument (national Swedish sample).

There is a basic problem of interpretation in all conservation tasks of this type, namely, what is the question the pupils are actually answering? Naturally, one can claim that mass is being asked for in the conventional manner, and that the problem therefore measures whether the pupil understands conservation of mass or not. (Swedish pupils are taught the difference between mass and weight in Form 7. The units 1 kg and 1N are introduced. Weighing is practised as a way of determining mass.) But the pupils do not always act in accordance with the scientist's intentions, as shown by the following problem and a pupil's response. "200 g of sugar are added to 1000 g of water in a pan. The water is stirred until the sugar dissolves. The contents of the pan will now weigh----"The pupils had to tick one of the alternatives supplied. A pupil who chose the alternative "More than 1000 g but less than 1200 g" writes as follows: "The water must weigh more if you add something. Even if the sugar has dissolved, there is just as much sugar in the water (as much as you poured in). But I don't think it weighed exactly 1200 g, because when the sugar dissolves into small grains, its density must be less". (See Andersson, 1984). This answer indicates that the pupil conserves amount of matter, but not weight. He associates our request with 'heaviness' instead of amount of matter.

As far as the phosphorus problem is concerned, about 25% of the pupils claim that smoke or gas does not weigh anything, is light or lighter than a solid. (See Andersson, 1984, for details). They draw different conclusions according to what stage of the given process attracts their attention. If they particularly notice that white smoke is formed, they believe that the weight is less than 205 g - the phosphorus has been transformed into something that is lighter. If they focus their attention on the stage where the white smoke dissolves in the water, they answer that the weight is still 205 g. It is then tacitly understood that while white smoke is present, then the flask weighs less than 205 g. (It might be so that some of these pupils are thinking further than those who say that the weight is unchanged because the vessel is sealed. They are beginning to analyse the details in the process and then get easily tangled up in difficult problems.) It can be said of these answers that we do not really know what the pupils' conceptions of the amount of matter are. Probably, at least some of them consider that the amount of matter is unchanged, but not the weight. One would need to interview each pupil individually to achieve further clarification. In other answers, on the other hand, it is obvious that the pupils do not conserve the amount of matter. This applies chiefly to answers expressing that matter disappears or is transmuted into energy.

The difficulties of interpretation just discussed apply to all the test problems with complex transformations that the pupils were given, and they are not easy to eliminate. A problem about conservation of mass must in one way or another be made operational, and then some weighing procedure seems reasonable. To the pupil this may mean that a question about mass is interpreted as one about weight or 'heaviness'.

Conservation of weight

Some test problems have been directed towards finding out about pupils' understanding of weight. (Piaget, 1974 pp 85-94; Minstrell, 1982; Watts, 1982). Some important results are summarised in table 1.

Table 1 Everyday and scientific concepts of weight.

EVERYDAY CONCEPTS	SCIENTIFIC CONCEPTS
Weight is determined by the measuring method, incl. what one's own body feels.	Weight is given by Newton's Law of Gravitation.
The force of gravity is associated with free fall, weight with objects feeling heavy.	Weight and the force of gravity are the same thing.
The weight of an object - increases with the height above ground.	The weight of an object - decreases with the height above ground.
- depends on how the objects are placed on the scales.	- does not depend on how the objects are placed on the scales.
- increases if the object is compressed and decreases if it is spread out.	- does not depend on whether the object is compressed or spread out.
- disappears if the air disappears	- is independent of whether there there is air or not.

The everyday thinking presented in table 1 is a significant feature among the pupils in the age-group 11-15 years, but no systematic survey in which written problems are given to large samples has been carried out. The two columns in table 1 provide some clue as to the level of abstraction that pupils are required to reach before mastering the weight concept of science.

Comments

The comments regarding the continuum conception of matter that were given in the previous sections are also valid for the results of experiments concerning conservation of amount of substance. Clearly, Piagets conclusion that conservation of amount of substance is mastered by pupils from the age of 7-8 years has to be revised. This type of conservation reasoning is not a general ability, but dependent both on the individual's conception of matter and of weight.

2.4 Solid, liquid and gaseous state

The studies dealing with states mainly apply to gases, particularly air (Séré, 1982, 1985, 1986; Stavy, 1988). Stavy and Stachel (1985b) have investigated pupils' conceptions of "solid" and "liquid". Information may also be obtained from other studies with regard to pupils' conceptions of the three states, especially the gaseous one. However, they do not focus on the states as such, but on chemical reactions, changes of state, conservation of the amount of matter and the particulate nature of matter, so that they are dealt with in other sections of this paper.

Solid and liquid state

As already mentioned, some aspects of pupils' conceptions of solid and liquid have been investigated by Stavy and Stachel (1985b). One of the tasks given to Israeli children aged 5-12 was to sort 30 objects into the groups "solid" and "liquid". The objects represented five categories, namely, rigid bodies, soft objects, powders and thin and dense liquids. Among the results we note that soft objects are sorted correctly by only 50% of the 12-year-olds. Powders are the most problematic. Up to 60% of the pupils placed them in the "neither solid nor liquid" group. The authors point out, "...if children do not possess these concepts (solid and liquid), or understand them differently than the adult, it is entirely useless to explain them on the basis of the particulate theory, since these childen will not be able to grasp the problem that this theory explains."

The gaseous state

The majority of the studies concerned with the gaseous state apply to air. When acquainting oneself with the results, one should bear in mind that pupils at primary and lower secondary levels seldom regard air as an example of a gas but consider gas and air to be two separate things. Gas is associated with something poisonous, injurious or inflammable, such as war gas, exhaust and Calor gas. Air is associated with breathing and life. Nor do upper school pupils have any clear idea that gas is a superordinate concept to air and that air is a mixture of different gases. They say, for example, that "air is oxygen and gas" or that "oxygen is something you breathe, air that is" (Andersson & Renström, 1981).

Séré has demonstrated that at least half of a group of French 12-year-old children, before instruction, do not understand that air can be delimited and enclosed and that air has weight. Another significiant difficulty is to distinguish between amount of substance and volume. Séré (1985) has also interviewed pupils aged 12-13 years about a blood-pressure gauge applied to their arm. So long as the armband was pumped up, the pupils considered that the air was pushing, exerting or producing a pressure. But when the tester stopped pumping, all the pupils thought that the pressure ceased even though the armband was obviously compressing their arm. In another experiment, air was injected into a flask through the cork by means of a syringe. At the bottom of the flask there was a little capsule, covered with an elastic membrane. The pupils predict that when the piston is pushed in, the air in it flows down into the flask and affects the membrane so that it bulges into the little capsule it covers. But some claim that when the piston is completely pushed in, there is no longer any air to flow, so that the membrane returns to its initial position. But, in fact, the inward bulge remains because the pressure of the gas has increased. Most pupils also predict that, if the capsule is upside-down, the membrane will not be affected when the piston is pushed in, which is also contrary to what actually happens.

Andersson and Eliasson (1988) have found that 75% of 51 students in grade 7 (13 years old) predict that air in a syringe is incompressible. Andersson (1983) reports about students' explanations of the well-known experiment in which a balloon is stretched over the mouth of a vertical glass flask which is heated from below. The great majority of about 400 students in grade 7-9 believe that the balloon rises because of the warm air rising and filling it up. Nussbaum (1985) connected a hand evacuating pump to a one litre flask containing air. The pump was operated for a few seconds in order to evacuate some air from the flask. Some students (14 years old) think that after pumping the upper half of the flask is empty and the lower one filled with air. Other students believe that the lower part is empty and the upper one filled with air.

Comments

In the studies described there are indications that matter is conceived as continuous and static. An explicit expression is that air is "all one thing, a single mass", given as an explanation why air cannot be delimited and collected (Séré, 1985). The idea that air exerts pressure on its surroundings only when it is in macroscopic motion may be regarded as a result of conceiving matter as static. If a thing is static, it cannot exert pressure. On the other hand, the notion of air expanding, filling the flask-balloon system, is not compatible with the static continuum conception. Therefore, the students are inclined to believe that air moves from the flask to the ballon. And if some air is removed from a flask, it is natural to think that the rest, which is assumed to be continuous and static, stays at the bottom or perhaps rises to the upper half of the flask. Something static doesn't spread quickly in all directions. And why should continuous matter, filling every corner of a certain space, be compressible?

3. PUPILS' CONCEPTIONS OF ATOMS, MOLECULES AND SYSTEMS OF PARTICLES

Pupils' conceptions of atoms and molecules have been studied, analysed and commented on by Dow, Auld and Wilson (1978), Pfundt (1981), Andersson and Renström (1981), Nussbaum and Novick (1982), Nussbaum (1985), Shollum, Osborne and Lambert (1982), Eylon, Ben-Zvi and Silberstein (1982), Ben-Zvi, Eylon and Silberstein (1982, 1986), Andersson (1984), Brook, Briggs and Driver (1984), Meheut et al. (1985), De Vos and Verdonk (1987a) and Renström (1988). To form a pattern out of all the empirical details is no easy task. Some essential lines may, however, be distinguished.

3.1 The atom - a primary building-block or the final link in a process of division?

Pfundt (1981) made the surprising observation that the pupils in her own class (Form 10, "Realschule") conceived of the atom as the final link in a process of division, not as a primary building-block that exists in matter all the time. Since division is somewhat arbitrary, the atoms, the pupils thought, could vary in form, for instance, they could be square or rectangular. And there is no vacuum between them. These observations inspired Pfundt to systematically investigate to what extent the pupils spontaneously imagine that matter consists of building-blocks that are there all the time, in contrast to particles that appear temporarily, for instance, through division. Forty-nine pupils in Forms 7, 8 and 9 were interviewed. They had not had any lessons about atoms and molecules. Very few of them conceptualised matter as consisting of primary building blocks. Pfundt concludes that it is natural for the pupils to think of matter as a continuum. The continuum can sometimes be divided up into small particles, but these do not exist from the beginning as primary building-blocks, but are formed from the continuum under certain conditions. Since adults also respond in the same way as the pupils do before they have attended any lessons, one can, according to Pfundt, assume that school does not prevail upon the pupil to abandon his everyday continuum model in favour of the atomic one.

3.2 Conceptions of atoms and molecules - macroproperties are transferred to the microworld.

If pupils conceive the smallest units of matter to be the final stage in a process of division, it is perhaps not so surprising that they project macroscopic properties onto atoms and molecules. Here are some examples: phosphorus is yellow - phosphorus atoms are yellow, naphthalene smells - naphthalene atoms smell, the water is hot - its molecules are hot. The projection of macroproperties onto the microworld is also seen when transformations of matter are under discussion. This means that the models disappearance, displacement, modification and transmutation are applied to atoms and molecules.

A. Disappearance

This is how a pupil explains the iron wool experiment (Andersson & Renström, 1981). "Those atoms or whatever-you-call-them (can't remember) burn up, and then the wad of iron wool doesn't weigh anything any more. Not sure of the answer".

B. Displacement

Characteristic of the macroscopic application of this model is that the substances are unchangeable as regards their properties. In the micro-world it is the molecules that are conserved. When a pupil has to explain how a copper pipe that was initally shiny became tarnished, he writes: "The metal molecules that exist in the air have fastened onto the pipe and form a coating". It is thus a question of an addition, not a chemical reaction (Andersson & Renström, 1983a). Eylon, Ben-Zvi and Silberstein (1982) report that it is relatively common that pupils conceive a new molecule to be the result of adding together or mixing the initial molecules. In other words, there is no reference to the original molecules disappearing and new ones forming, but to the old molecules remaining and forming parts of the new ones. It is a question of displacement of unchangeable molecules. Some of the pupils tested by Eylon et al. (1982, form 10, 15 years old) claim, for example, after six months of chemistry teaching, that for N_2O_5 to be formed, N_2 and O_5 have to be among the reactants. Again when interviewing fifteen-year-old pupils after chemistry lessons, Shollum (1982) found that a fair number of them see precipitation as an adding together of the original particles.

C. Modification

Characteristic of the macroscopic application is that substances are modified with respect to certain properties, but that the identity of the substance is conserved. In the microworld it is atoms and molecules that are modified during, for example, chemical reactions and phase changes. De Vos and Verdonk (1987a) asked pupils, 14-15 years old, who were investigating how rust is formed to describe a rust molecule. Some of them drew a brown circle and stated that the interior of the circle was iron and its circumference rust, which was perceived as iron with some of its properties altered. The authors also report that a number of pupils believe that alcohol and water molecules cannot be solid objects but must be small drops. They also say that the molecules in a soft substance (e.g. hot stearin) must also be soft. "A soft substance cannot be made of hard molecules".

D. Transmutation

This is how a pupil explains the iron wool experiment (Andersson & Renström, 1981). "It has something to do with electrons, or plutons...neutrons. It changes itself to a new substance that has more plutons in its molecule. Aha! I think that for an old steel atom there is a new... a new carbon molecule. All those molecules are heavier".

3.3 Systems of many particles

Pupils have, in various connections, drawn, described and discussed systems of many particles. From this, Nussbaum (1982) and Renström (1988) have formulated some categories.

A. Atoms/molecules/particles are placed in continuous matter like raisins in a cake

One example is provided by a pupil in Form 8 with whom Renström discusses the structure of a grain of salt. The pupil draws the outline of a grain of salt with quite a number of dots scattered in it. He calls the dots molecules. When the interviewer asks if there is anything in between, he answers salt. There are several variants of this category. In some cases the continuous medium is the substance and the particles something else. In other statements, the particle system is the substance and the medium something else, often air.

The category may be seen as evidence of a conflict between everyday and scientific reasoning. In school the pupils have been taught that there are atoms and molecules in objects but, nevertheless, do not abandon their everyday reasoning. One solution to this dilemma is to retain the idea of a continuum in the form of a homogeneous substance, and to pay regard to what they are taught in school by placing atoms and molecules within it. In this way, as Renström points out, the pupils solve the problem of bonds. Without a medium the atoms would roll apart like marbles. The category may also reflect a difficulty in imagining empty space or vacuum.

In some of the pupils' answers the material status of the atoms and molecules is unclear. Are they something other than matter? To obtain further information on this, the following written problems were given to 491 pupils in Forms 7, 8 and 9 (Andersson, 1987). "In school you get to learn about *matter*. Is alcohol matter? Is a bun matter? Is a cat matter? and so on. Underline in the list below what is matter!" Then followed 30 examples both of what is material and immaterial. The pupil was asked to explain his/her reasoning. More than 70% (no age trends could be observed) are of the opinion that solid objects, food and organisms, are matter. But only between 40 and 50% consider that atoms and molecules are matter. Some pupils have written explanations. They claim, for example, that you can touch matter and weigh it. Since you cannot do this with atoms and molecules, they cannot be matter.

B. Conglomerate of particles

In this category the particles are so tightly packed that there is no space in between. This applies regardless of whether the solid, liquid or gaseous state is concerned. The particles can vary in size in a given substance. They can coalesce and form larger units. They can also disintegrate into smaller particles, which in their turn disintegrate into even smaller ones, and so on. Nussbaum points out that by filling space with a conglomerate of particles the pupils avoid a vacuum in their answers despite being taught about it.

C. Systems of many particles with macroscopic properties
This category may be seen as a combination of the idea of many particles with the conception that atoms and molecules have properties that are similar to those of the substance. (In the two previous categories few properties besides existence were attributed to the particles. Occasionally motion was mentioned.)

The three categories just described are not models of matter in a hypothetico-deductive sense. The pupils do not have any conscious models that they attempt to develop in an interplay with observations. On the contrary, they appear to change the properties of their particle collectives from one situation to the next. If wood burns, then wood particles may also burn. If phosphorus melts, then the phosphorus atoms are also assumed to melt. If water solidifies, this can be explained by the molecules in the continuous substance water ceasing to move. And so on.

Other observations have been made of pupils' conceptions of systems with many particles. Dow et al. (1978) have shown that both compulsory school pupils (after lessons on the particle nature of matter) and physics teachers draw particle systems corresponding to solid, liquid and gaseous states so that the relative distance between two adjacent particles is 1:2-3:6-7. The distance in the solid state is set at one unit. The correct proportions are 1:1:10.

It has also been observed, by Ben-Zvi et al. (1982), that pupils have difficulties in coordinating macroscopic conditions, structures of individual molecules and properties of particle systems simultaneously. One of the tasks they have given to pupils (Form 10, after six months' chemistry teaching) is "The following is a schematic drawing of a closed erlenmeyer vessel which contains the gas Cl_20 at room temperature. Draw the contents of the vessel!" (When being introduced to the task, the pupils were instructed to use a round circle labelled Cl to represent a chlorine atom, and a similar circle for an oxygen atom). It turned out that 29% only drew *one* molecule. A similar task concerned O_3 and I_2 in two vessels. The first element was assumed to be in the gaseous state, the second in the solid one. 8% placed three oxygen atoms as far away from each other as possible in the vessel, but two iodine atoms close together. The authors interpret this to mean that the pupils have not succeeded in distinguishing between the molecular and the particle system aspects. They transfer what they have learnt about systems of particles to individual molecules. In connection with other tasks, it was sometimes found that up to 25% used expressions such as "a copper atom in the solid state".

4. SOME IMPLICATIONS FOR TEACHING

The implications for teaching of the research results presented above depends to some extent on the level of description one focuses on. Let us first put the emphasis on level IV (see introduction). At this level matter is, in *everyday thinking*, conceived as continuous and static. There is no vacuum. Thinking is directed towards the concrete and observable. This conception may be thought of as a framework that gives a certain direction to thinking about matter. The transformation models: disappearance, displacement, modification and transmutation may be looked upon as a pool of ideas compatible with this framework. The choice from the pool in a specific problem situation depends, among other things, on contextual factors and, at least for younger children, on developmental level (see Bar, 1987).

In *scientific thinking* matter is conceived as particulate and dynamic. Between the particles there is vacuum. The dynamic particles are considered as a model related to the observable world in a hypothetico-deductive way, which means that scientific thinking about matter takes place at two different but related levels. Think, for instance, of mercury and oxygen, which under suitable conditions form mercury oxide, which in its turn can be decomposed. When mercury and oxygen interact, the substances mercury and oxygen cease to exist. A new substance is formed instead, namely, mercury oxide. The new substance does not contain the substances mercury and oxygen. But, perplexing though it may seem, it is possible to retrieve them from the mercury oxide. How can the mercury oxide "remember" what existed initially? In chemistry this mystery is explained with the model of indestructible atoms that retain their identity (same atomic number) but which can be combined in new ways. The new combination ($2Hg+O_2 \rightarrow 2HgO$) explains why the old substances disappear and a new one is formed. The conservation of atomic identity explains why the original substances can be retrieved ($2HgO \rightarrow 2Hg+O_2$).

The research results described in this paper give some insight into the learning difficulties the pupils have when trying to move from everyday to scientific thinking. Firstly, the students have many alternative conceptions relating to the macroscopic world - gases don't have weight, powders aren't seen as examples of the solid state etc. Secondly, there are many problems with the world of atoms and molecules, e.g. projection of macroproperties onto atoms and molecules (atoms and molecules are treated as equal in kind to substances, there is no model-observation distinction), placing atoms and molecules in continuous matter (continuum conception still dominant) and filling space with a conglomerate of particles (a way to avoid vacuum).

This level IV picture of students' reasoning about matter, including a description of their difficulties in understanding school-science, is a new instrument for taking a critical look at text-books, which reflect teaching practice.

Criticism of textbooks in physics and chemistry

As far as Swedish physics and chemistry books for grade 7-9 are concerned, atoms and molecules are seldom taken up as a model in the hypothetico-deductive sense. Instead, the pupils are required to learn "facts" about atoms and molecules, in the same way as they have to learn "facts" about the observable world. (The books that describe the theories of physics and chemistry are usually called "Fact books".) Whatever the reason for this may be, the presentation in the text-books is incomplete and sometimes probably confusing for a person with no scientific training. Let us take some examples.

A. Many different atomic models

Atoms and molecules are depicted in a variety of ways, including circles, balls, a nucleus and shells, balls separated by springs or pegs. The authors probably assume that the pupils understand that it is a question of different models with different purposes - sometimes one wants to show how the atoms rearrange themselves when chemical reactions take place, sometimes the structure of crystals, sometimes bonds, etc. But the many different models given without any explanation may confuse pupils whose basic tendency is to treat atoms and molecules as equal in kind to substances. It would seem that the only possibility of sorting this problem out is to make a distinction between model and observation and to provide an explicit explanation of the nature of the model concept.

B. Category mistakes

A relevant point is that, in their use of language, text-books (and teachers?) do not maintain a clear distinction between substances and atoms/molecules. Assume, for example, that the chemistry teacher says that water consists of hydrogen and oxygen. He or she is then thinking of the water molecule, which consists of two hydrogen atoms and one oxygen atom. But the pupils, who use their everyday concepts, can easily take the statement to mean that water is a mixture of the substances hydrogen and oxygen. Macroscopically, it is incorrect to state that "water consists of hydrogen and oxygen". Water is water and nothing else. It has neither the properties of hydrogen nor those of oxygen, but is a unique substance. If one wants to help the pupils to distinguish between model and observation, then it is necessary to choose one's words with care. In Swedish chemistry books for the upper level, you can read, in analogy with the example discussed above, that "out of all the elements in the earth's crust eight account for 97 per cent of the mass" and that "minerals that contain metals and are worth refining are called ores". This problem has been analysed by Selley (1978). He calls his article "The confusion of molecular particles with substances" and provides numerous examples, including "hydrogen ions are reduced to hydrogen gas". Selley's remarks are made mainly within the framework of chemistry. By linking them to research into students' reasoning a new dimension of significance is added.

It is undeniably tempting to link up these category mistakes in textbooks with the answers given by pupils. The idea that molecules are placed in continuous matter like raisins in a cake may be regarded as a mixture of the substance and the molecular levels. During a lesson Renström (1988) observed the model of a substance that is illustrated in figure 1. It is a molecular carbon chain interpersed here and there with small lumps of fat.

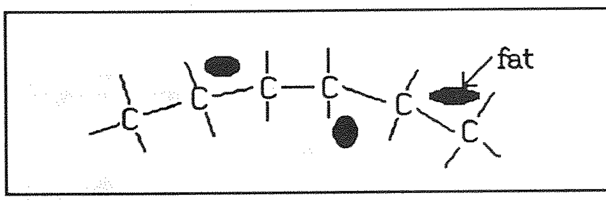

Fig. 1 A pupil's statement showing a mixture of categories.

From this there is only a short step to a very common type of textbook illustration. Look at figure 2! We can see water molecules floating about

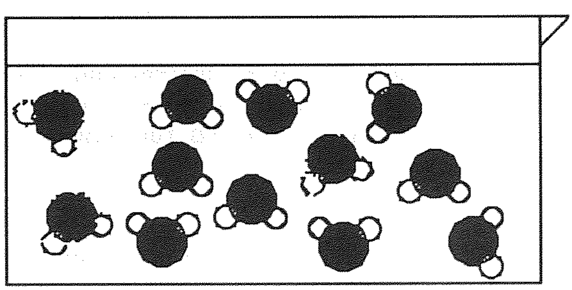

Fig. 2 Molecules in a liquid. Example of a type of textbook illustration.

in water. Pupils, who do not distinguish between model and observation, conceive matter as continuous and have difficulty in imagining empty space, can easily take this illustration literally and think that both ordinary water and molecules are present in the beaker. Perhaps this type of illustration helps to create the raisin cake category.

C. Distance between particles

Look at figure 3A. It is taken from a Swedish chemistry book and shows a piece of potassium in a flask with chlorine gas. The molecular picture is given in the two circles. We note that the distance between the particles is the same for chlorine in the gaseous state and potassium in the solid one. A more correct proportion would be 10:1. Then look at the model of salt taken from a physics book - Figure 3B. This type of crystal model is common. We note that the distance between the particles is 5-6 particle diameters, which indicates a gaseous state. We get the anomaly "gas with molecules in perfect order".

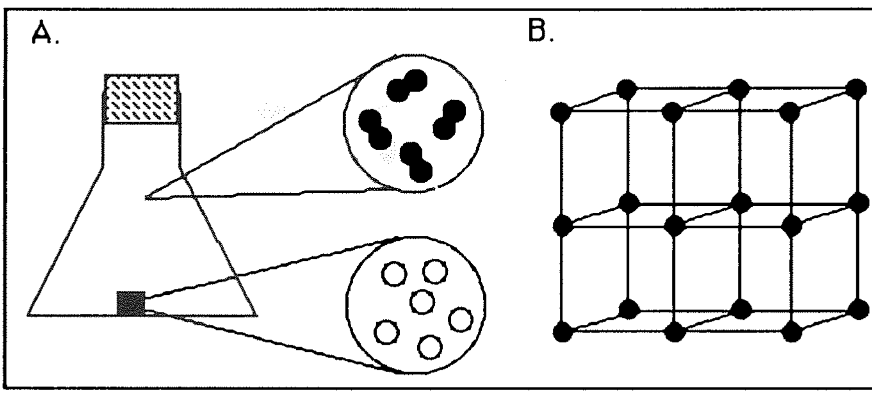

Fig. 3 Textbook illustrations with questionable particle distances.

If the pupils are trying to build up a coherent and consistent model of matter, then they must be confused, because in other connections the distance between the particles is presented for solid, liquid and gaseous states in a correct fashion.

D. Reaction formulae

A common technique for clarifying a chemical reaction is to use circles of different colours. See figure 4.

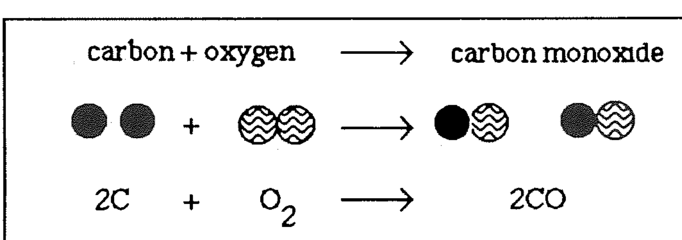

Fig. 4 Different ways of symbolising a chemical reaction.

remarks are made mainly within the framework of chemistry. By linking them to research into students' reasoning a new dimension of significance is added.

It is undeniably tempting to link up these category mistakes in textbooks with the answers given by pupils. The idea that molecules are placed in continuous matter like raisins in a cake may be regarded as a mixture of the substance and the molecular levels. During a lesson Renström (1988) observed the model of a substance that is illustrated in figure 1. It is a molecular carbon chain interpersed here and there with small lumps of fat.

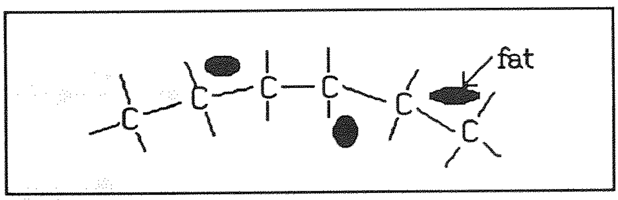

Fig. 1 A pupil's statement showing a mixture of categories.

From this there is only a short step to a very common type of textbook illustration. Look at figure 2! We can see water molecules floating about

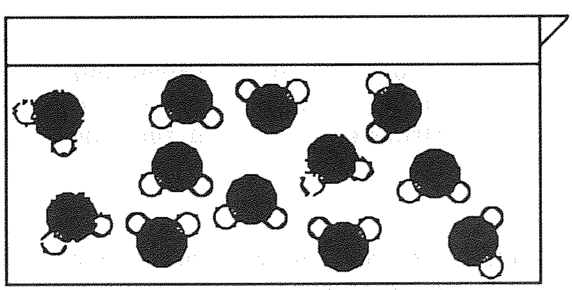

Fig. 2 Molecules in a liquid. Example of a type of textbook illustration.

in water. Pupils, who do not distinguish between model and observation, conceive matter as continuous and have difficulty in imagining empty space, can easily take this illustration literally and think that both ordinary water and molecules are present in the beaker. Perhaps this type of illustration helps to create the raisin cake category.

C. Distance between particles
Look at figure 3A. It is taken from a Swedish chemistry book and shows a piece of potassium in a flask with chlorine gas. The molecular picture is given in the two circles. We note that the distance between the particles is the same for chlorine in the gaseous state and potassium in the solid one. A more correct proportion would be 10:1. Then look at the model of salt taken from a physics book - Figure 3B. This type of crystal model is common. We note that the distance between the particles is 5-6 particle diameters, which indicates a gaseous state. We get the anomaly "gas with molecules in perfect order".

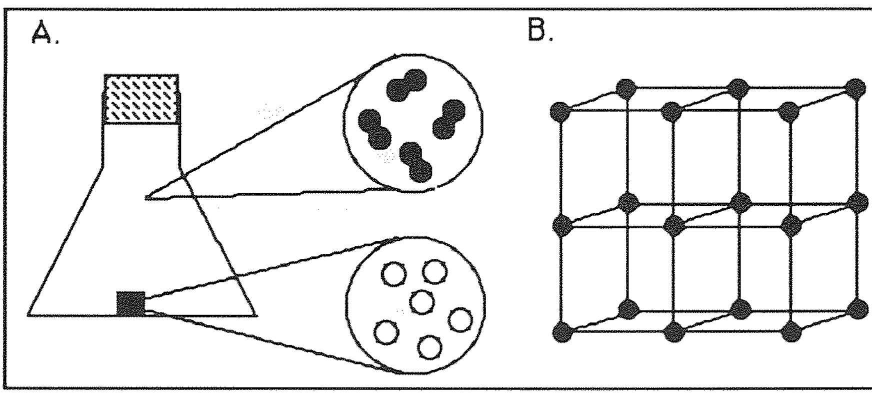

Fig. 3 Textbook illustrations with questionable particle distances.

If the pupils are trying to build up a coherent and consistent model of matter, then they must be confused, because in other connections the distance between the particles is presented for solid, liquid and gaseous states in a correct fashion.

D. Reaction formulae
A common technique for clarifying a chemical reaction is to use circles of different colours. See figure 4.

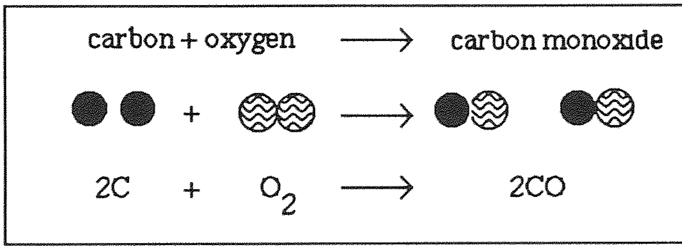

Fig. 4 Different ways of symbolising a chemical reaction.

The advantage is that these help to keep the different atoms in a reaction in order (carbon is black and oxygen red in the textbook in question). The disadvantage is that they may communicate an additive conception. You obtain a visual impression that the carbon monoxide molecule is one oxygen and one carbon atom added together rather than a new particle with other properties than both the atoms included. Compare the section about atoms and molecules where evidence was provided that, after receiving instruction, some pupils think additively rather than interactively about the formation of molecules.

With reference to figure 4, it should also be pointed out that it is relatively rare that textbooks symbolise chemical reactions with particle systems, which would provide a truer picture of what happens and suitable training in chemical reasoning.

To see the textbook through the eyes of the pupil

Hopefully, the examples above have shown that studies of pupils' thinking can stimulate us to look critically at textbook praxis. Some further observations now follow that are not so generally applicable as the ones described so far, but which are nevertheless thought-provoking. Look at figure 5, illustrating electrolytic purification of crude copper. Having taken note of Pfundt's (1981) observation that pupils believe that atoms are created out of continuous matter, one may certainly wonder whether this illustration helps to confirm this everyday conception.

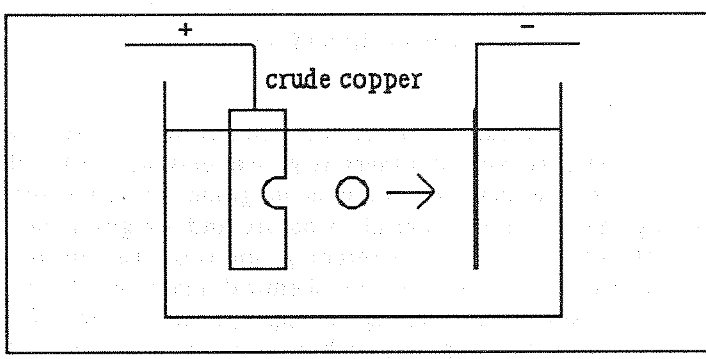

Fig. 5 Textbook illustration: electrolysis of crude copper.

One last example. In a physics book for the upper level we can read the following: "An iron atom is the smallest part of the element iron which still has the properties of the substance. A lead atom is the smallest part of the element lead, and so on." An analogous description may be found in a well-known Swedish encyclopaedia: "The atom is the smallest part of an element that possesses the characteristic properties of the element." On the basis of definitions such as these, the pupils can draw conclusions like:

- Since iron expands when heated, the iron atoms also expand.
- Since iron can melt, the iron atoms can also melt. And so on.

Compare what has been said earlier about how the pupils transfer macro-concepts to the world of atoms.

In sum: the analysis based on recent research results demonstrates that there is room for specific improvements of textbooks (and probably also teaching practice) when it is a question of illustrations, language and the model-observation relationship.

Conservation

If we move down from level IV descriptions of pupils' thinking of matter and its transformations, other implications for teaching become evident. It was demonstrated in a previous section that conservation of mass and weighing as a method of determining mass hold considerable conceptual difficulties for the pupils. But in Sweden, and probably in other countries as well, teaching appears to be based on the tacit assumption that these difficulties do not exist. In any case, the textbooks seldom take up problems like the ones discussed in this section. It might be necessary to change prevailing practice. In actual fact, the many alternative answers the pupils give indicate that it might be necessary to discuss conservation of mass in connection with practically every experiment in chemistry and many in physics as well. The principle of the conservation of mass should be so firmly fixed in the mind of every citizen that no person can believe that it is possible to get rid of refuse simply by burning it, or dumping it in water so it becomes diluted and disappears.

The gas concept

The studies mentioned earlier about the gaseous state (Séré, 1982, 1985, 1986; Stavy, 1988), as well as others (e.g. Andersson, 1984), clearly demonstrate that the majority of students in grade 7-9 have difficulty in understanding that a gas is material in nature and weighs something, that there are different gases with different properties, that air is a mixture of gases and that gases take part in chemical reactions. Great care has therefore to be taken in developing an appropriate concept of gas, starting from very elementary aspects, such as experiencing the existence of a gas, e.g. air, and separating volume from mass (Boyle's law must be rather incomprehensible if one believes that the mass and volume of a gas in a syringe covary.) The studies referred to offer many interesting and specific ideas about how this might be done.

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STUDENTS' REASONING IN THERMODYNAMICS

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1. INTRODUCTION

Thermodynamics is a subject which involves multivariable problems. The behaviour of a huge number of particles is described using a small number of variables, which are mean values or macroscopic quantities. These variables can be linked, at thermodynamic equilibrium, by certain relationships, for example PV=NRT for perfect gases. In any transformation, such relationships hold for initial and final equilibrium states. In *transformations* considered as *"quasistatic"*, these relationships hold as well for any intermediate state, then also considered as equilibrium states. That is to say that we have to consider *several variables*, most of the time more than two, *changing simultaneously* under the constraint of one or several relationships.

Such a mental activity a priori raises obvious difficulties. Piaget and Inhelder (1941) have shown that children, dealing with three kinematic variables (s,v,t), in fact consider one of these quantities as linked to a single other one: "the faster, the further". Other studies (Viennot, 1982; Maurines, 1986) show similar difficulties.

In this paper, we will illustrate, in the domain of thermodynamics, how students, and others, commonly reduce the intrinsic complexity of such problems. These tendencies towards "functional reduction" in common reasoning, will be shown to range from a simple reduction in the number of variables considered to a more elaborate procedure where all the variables are taken into account, but in a simplified way: the "linear causal reasoning".

The experimental facts supporting our analysis come from a study by Rozier (1987). The students in the study (N≅2000) were drawn from three types of courses: one of the four first years at university of Paris 7, a selective course preparing french "grandes écoles d'ingénieurs" (two years after baccalaureat) and teachers (N=29) in in-service training sessions. After undertaking exploratory interviews (N=9), this study was conducted mainly on the basis of written questionnaires (14, only 4 of them are quoted here, many results being left aside for the sake of brevity). Because of the similarity of results for the different sub-samples we do not report the results for each separately. We will also quote excerpts from textbooks, popular science books and research papers in science education, as well as teachers' reactions in training sessions, in order to show to which extent and according to which modalities students' common ways of reasoning are shared by different categories of professionals in science.

The pedagogical implications finally discussed will relate mainly to our teaching goals.

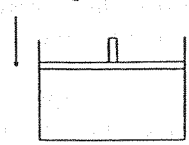
2. REDUCING THE NUMBER OF VARIABLES

a. Forgetting some of them

A first question will illustrate students' most general and obvious tendency in coping with multivariable problems, which is to forget some relevant variables. Table 1 summarizes the question posed (a written test) and the most frequent response. Asked to explain in molecular terms why pressure increases in an adiabatic compression of a perfect gas, 43% students say, for instance:

Table 1 Questions about an adiabatic compression (see Rozier, 1987), correct and typical responses.

QUESTION:



An adiabatic compression of a perfect gas: pressure and temperature both increase. Can you explain why in terms of particles?

notations used below: volume of gas:V, number of particles per unit volume: n, pressure of gas: p, temperature of gas: T, mean speed of particles: v, mean kinetic energy of particles: e_c, heat :Q, $\nearrow$:"increases", $\searrow$:"decreases", $\lrcorner$:"is produced", $\longrightarrow$:"therefore" (see text)

p outlines of ....

...correct explanation:

$$V\searrow \longrightarrow \begin{bmatrix} n\nearrow \\ \text{and} \\ v\nearrow \end{bmatrix} \longrightarrow \begin{bmatrix} \text{number of collisions per.....} \nearrow \\ \text{and } v \nearrow \end{bmatrix} \longrightarrow p\nearrow$$

...common explanation:

$$V\searrow \longrightarrow n\nearrow \longrightarrow \text{number of collisions} \nearrow \longrightarrow p\nearrow$$

T outlines of ....

...correct explanation:

$$V\searrow \longrightarrow v\nearrow \longrightarrow e_c\nearrow \longrightarrow T\nearrow$$

common explanation:

$$V\searrow \longrightarrow \text{number of collisions} \nearrow \longrightarrow Q \lrcorner \longrightarrow T\nearrow$$

"Volume decreases, therefore molecules are closer to each other, therefore there are more collisions, then pressure increases".
"Volume decreases, therefore there are more molecules per unit volume, then pressure increases".
These responses may be outlined in the following way:

$$" V \searrow \rightarrow n \nearrow \rightarrow p \nearrow "$$

In these comments, an increase in pressure is ascribed only to an increase in the "number" (per unit volume, which is often implicit) or "density" of particles. Nothing is said about the other relevant aspect, from a kinetic point of view, i.e. the mean speed of particles (see correct answer outlined in table 1). Other questions in this study confirm this preferential link between pressure and "number of particles". In what follows, we will refer to such links as "*preferential associations*" between two variables.

Such a tendency in reasoning is not limited to students. As an example, let us quote an excerpt from a book of popular science (Maury, 1989) considered as very good by many physics university teachers (informal evaluation, in France): " Planes fly very high, at an altitude where molecules of air are much less numerous, and therefore the pressure of the external air on the window is much lower than at sea level. " This explanation may be summed up in the following way: $n \searrow \rightarrow p \searrow$, nothing being said about temperature. The same single variable dependency as in students' comments is observed, despite the fact that at the altitude considered, (≅10 km), the temperature is much lower than at sea level (≅70°C, i.e. a decrease of about 25% in temperature) which also contributes to the lowering of pressure. Teachers in different training sessions (N=55)[1] have been invited to criticize this comment. In every session, more than 95% accepted it without any modification, and when the change in temperature was pointed out, the great majoriry of teachers said that it was "not the important phenomenon", so it was not necessary to specify what happened to this quantity. Five pages further in the same book, the hot air balloon is presented and "explained" using the fact that when the temperature increases, it contains "less and less air". So the "number of particles ..." decreases. Yet in the hot air balloon, the pressure inside is not lower than that outside, due to temperature. No connection is made with the explanation previously proposed for low pressure outside the aircrafts.

Such ad hoc variations on the equation of state for perfect gases, PV=NRT, are typical of the inconsistencies introduced by the common tendency towards "functional reduction" and a call on preferential associations with no mention of other relevant variables.

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1. L.Viennot, Paris 1986-7, first cycle in secondary education (grades 6 to 9), N=30, training in physics; Milan 1989, all levels of teaching, N=25, training in didactics.

b. Combining together two variables
Reducing the number of variables may be obtained by another process also observed in other domains (Viennot, 1989a): two physical quantities seem to be "stuck together". This is the case, for instance, for mean distance between particles and mean kinetic energy of particles (Rozier, 1987). The name frequently used for this compound notion is "thermal motion", and its cement is the idea of disorder. In fact, only one of these quantities is determined only by temperature, namely the mean kinetic energy of particles. The other is also linked with other aspects: pressure, shape of potential of interaction between particles for solids and liquids. Students' reasoning and comments in this respect will be analysed in detail in what follows. Let us start, this time, with teachers' and researchers' quotations.

In the book previously mentioned, one may read: "particles need more room to move faster". In research reports, so called "accepted ideas" often give the impression of an adherence between these two - kinetic and geometrical - aspects. For instance, about thermal expansion (Lee, e.a., 1989):
"When a substance is heated, the molecules of the substance move faster and, therefore, move faster apart, which causes the substance to expand. In contrast, when the substance is cooled, the molecules move more slowly and move closer together, so the substance contracts."

Or, still more simply, a very commonly accepted idea is that thermal motion is much higher in gases (larger mean distance between particles) than in liquids (smaller mean distance between particles), and larger in liquids than in solids. See for instance these excerpts from french textbooks or written materials at university:
"In some solids, such as glass, and many plastics, molecules are squashed against each other and cannot move" (Sciences Physiques, 1980).
"when, cooling down a liquid, particles become motionless without any order, it is an amorphic solid" (DEUG SSM, 1985).

However, as said before, thermal motion, if meant as mean kinetic energy of particles, is only a matter of temperature. It is therefore the same for the water in the sea, the air just above, and a stone on the beach, in as much as they are at same temperature.

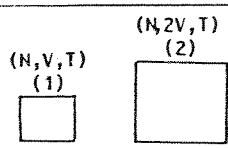
c. Lack of symmetry in implications
A striking feature in the way single-variable dependencies are commonly handled is a lack of symmetry in implications. Indeed, in the accepted theory of quasistatic transformations, variations are simultaneous and therefore, the implications are symmetrical (provided that the variables which are kept constant are specified).

A typical example is the following: the commonly accepted implication $V \searrow \rightarrow p \nearrow$, which was discussed above, seldom appears to be applied in reverse: $p \nearrow \rightarrow V \searrow$ (see below section 3).

This lack of symmetry may even occur in implications concerning some variables which are, most of the time, simply stuck together and therefore interchangeable in a symmetric relationship. This is the case for two variables evoked about the compound notion of "thermal motion": temperature and volume. As shown further in the paper, students are familiar with the $T \nearrow \rightarrow V \nearrow$ implication for a heated gas. But it is not so frequent at all, as classroom practice shows, to say that expanding a gas results in an increase in temperature.

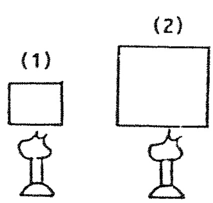
Another result also suggests, although indirectly, that students would not unconditionally reverse the preceding implication. A question proposed to students in Rozier's inquiry (see table 2) presents the following situation: an equal amount of heat is transferred to two systems consisting of same numbers of particles of perfect gases at same temperature, but in vessels of different volumes. 22% of students (N=255) or teachers (N=28) give responses equivalent to this one: "the amount of heat is more diluted in the larger vessel, so the temperature does not increase as much as in the smaller vessel", which can be summarised by "larger volume → smaller increase in temperature"

Table 2 A question from Rozier (1987) and corresponding rates of response.



Two rigid vessels (1) and (2) are filled with a perfect gas, in respective states (N,V,T) and (N,2V,T)

N= number of moles in each vessel
V= volume of vessel 1
T= temperature of each vessel



The two vessels are heated up for the same time with identical heat sources, then one measures their respective temperature.

Do you think that

	Rate of response (N=283)	
$T_1 > T_2$	37%	22% : "because $V_1 < V_2$"
$T_1 = T_2$	48%	30% correct justification
$T_1 < T_2$	5%	
I don't know	8%	

Why? ____________

In conclusion to this first section we suggest that common types of reasoning observed in students and teachers are characterised in the following way.

In the implications used, $\Phi_1 \rightarrow \Phi_2$, "$\Phi$" refers to *a phenomenon specified with only one variable*, for instance: "p increases", or "input of heat". When several variables are mentioned (see table 1), this is done through an argument which links the variables in a linear chain:

$$\Phi_1 \rightarrow \Phi_2 \rightarrow \ \Phi_n \rightarrow \ \ldots$$

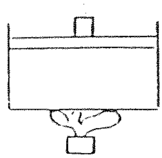
Each specific implication $\Phi_n \ \Phi_{n+1}$ does not imply that the reverse implication would be accepted by the same person. Students' responses to other questions will now introduce a new feature in the interpretation of such chains, which gives some coherence to these preliminary conclusions.

3. CAUSALITY AND CHRONOLOGY: LINEAR CAUSAL REASONING

A very common (43%, N=120 students) "explanation" of the increase in volume resulting from the heating of a perfect gas at constant pressure is of the following type (see question in table 3):

Table 3 A question about an irobatic heating of a gas (see Rozier, 1987), correct and typical responses.

QUESTION



A perfect gas is heated at constant pressure...Its volume and temperature both increase. Can you explain why?

Notations used below: see table 8, and: c_p: molar specific heat at constant pressure, R: constant, N: total number of moles, Δ: algebraic increment of...

Outlines of ....

correct explanation:

$$\left.\begin{array}{l} Q \text{ (supplied to gas)} = c_p \, \Delta T \\ \text{and } Q>0 \\ \text{and } c_p>0 \end{array}\right] \longrightarrow \left.\begin{array}{l} \Delta T>0 \\ \text{and} \\ PV=NRT \\ \text{and} \\ p, N, R, \text{ all constant} \end{array}\right] \longrightarrow \Delta V>0$$

common explanation:

$$\text{supply of } Q \longrightarrow \ T \nearrow \longrightarrow p \nearrow \longrightarrow V \nearrow$$

"The temperature of the gas increases. Knowing that in a perfect gas PV=NRT, therefore at constant volume, pressure increases: the piston is free to slide, therefore it moves and volume increases".
This response can be outlined in the following way: supply of heat $\rightarrow T \nearrow \rightarrow p \nearrow \rightarrow V \nearrow$ (with obvious notations).

In such comments, one of the evoked events, $p \nearrow$, contradicts data presented in the problem, namely that p is kept constant.
Such a contradiction, and others as we will see, disappears if one admits that this form of argument is interpreted temporarily. An arrow, then, does not mean only "therefore", but also "later". Table 4 shows how, in three and probably many other languages, these logical and chronological levels melt into a single word, totally ambivalent, in english: "then".

Table 4 Shift in meanings from logical to chronological levels.

level ↓	french	english	spanish
logical	donc	therefore	por eso
intermediate	alors	then	entonces
chronological	ensuite	later	despues

From this point of view, the previous chain subdivides into two steps:
- *first step*: "Supply of heat $\rightarrow T \nearrow \rightarrow p \nearrow$", volume being implicitely or explicitely kept constant. Notice that such a constancy of volume is a sufficient condition for the two first implications to be straightforward. At constant volume, an input of heat, in the accepted theory, necessarily results in an increase of temperature (no work being transferred to the exterior of the gas). The same condition also allows the otherwise not obvious conclusion that if temperature increases, then pressure increases.
- *second step*: "$p \nearrow \rightarrow V \nearrow$". The piston is now released (this is said explicitely by some students) and moves until the internal pressure equals the external one. In such a chronological view, the seemingly contradictory argument "$p \nearrow$ (during isobaric heating)" becomes acceptable, as well as the statement "at constant V", followed by this other: "Volume increases". These events indeed are understood as *successive*, and therefore as *temporary*. So they seem no longer contradictory.

To sum up: this kind of response supports the hypothesis (see Rozier, 1987) that a linear type of reasoning is used:

$$\Phi_1 \rightarrow \Phi_2 \rightarrow \Phi_n \rightarrow \quad ..,$$

in which, as said earlier, each phenomenon Φ is specified with only one physical quantity, and where the causality referred to by the arrow has a both logical and chronological content. The temporal connotation of such an implication accounts for the lack of symmetry described in section Ic. This way of reasoning contradicts the accepted theory of quasistatic phenomena, in which all the changing physical quantities are supposed to change *simultaneously* under the *permanent* constraint of one or several relationships. But this enables variables to be coped with two by two, and to say different things about one of them at different stages of the argument.

Other inconsistencies become acceptable in this linear causal reasoning, as we will see now.

4. LINEAR CAUSAL REASONING AND THE PROBLEM OF STEADY STATES

Another question from this study (Rozier, 1987) puts in evidence how the features of linear causal reasoning just described fit in with students' most common responses and allow comments which in the accepted theory lead to contradictions. Asked to explain in molecular terms why an adiabatic compression of a perfect gas results in an increase of temperature (see question in table 1), 42% of students (N=140) give comments of this type:

"When the piston is pushed down, volume decreases, therefore particles are closer to each other, whence more collisions occur between them.. and there is an increase in temperature".

"Same number of particles in smaller volume, then particles more squashed, more collisions, more heat produced".

"More collisions between particles, more energy produced due to friction"

These responses can be outlined as follows: $V \searrow \rightarrow n \nearrow \rightarrow$ number of collisions $\nearrow \rightarrow Q$ is produced $\rightarrow$ T $\nearrow$, the fourth statement being justified by the fact that "collisions produce heat".

Again a linear form is observed. Let us see now how the hypothesis of a temporal content is supported by this last comment: "collisions produce heat".

In such a comment, one can see an emergence of the well known preferential association between temperature and heat, an increase in temperature being necessarily ascribed, in common reasoning, to a supply of heat. One can also say that macroscopic properties of bodies colliding inelastically are ascribed to microscopic particles.

Valid as they may be, these interpretations do not explain how it is that none of these students realise the incompatibility between this statement: "collisions produce heat" and the idea of steady state. Indeed, if in an adiabatic vessel, collisions between particles were continuously producing heat, an explosion would soon occur. But if the statement: "collisions produce heat", or "there is some heat produced", refer to a temporary phenomenon, as in the "chronological" interpretation of students' reasoning, then there is no longer any incompatibility with the idea of steady state. Interestingly, some students in this inquiry, and others informally questionned in a class room, said that more collisions produced more heat, *during the transformation*, but that at the end of the transformation, the heat production stopped: the end of the argument is also the end of the story...

So, it seems that seeing the evoked phenomenon as temporary avoids the difficulties inherent to the analysis of steady states. Such states are not envisaged for themselves, but as the result of transitory phases, themselves analysed as step by step - variable by variable processes. All this is done, in common reasoning, without saying it, and probably without being aware of it.

Most probably, teachers share to a large extent this tolerance towards explanations incompatible (according to accepted logic) with steady states. Some teachers were asked, during training sessions (N=45)[2], to consider what answer they would give to a student who says "collisions between particles produce heat". *None* of them proposed a counter argument in terms of steady states.....Other examples of this teachers' tolerance are given in Rozier's study (1987, see also Viennot, 1989b).

5. INTERPRETING A COMMON IDEA IN TERMS OF LINEAR CAUSAL REASONING: CHANGES OF STATES AND THERMAL MOTION

As said before, an idea widely spread among students and teachers, is that thermal motion is more intense following the order: solid, liquid, gas. At first sight, this might be simply a manifestation of the adherence between mean kinetic energy and mean distance between particles commonly referred to by the expression "thermal motion" and cemented by the idea of disorder.

An experiment (Rozier, 1987) has been done with students at university to refine this point of view and to see if the linear causal reasoning was an help in interpreting common ideas in this field.

An excerpt from a textbook (Valentin, 1983) was first given to students, who were asked to read it carefully.

"Thermal energy possessed by each molecule is large enough to prevent the molecules of the gas from being bound: in a gas, molecules are continuously hitting each other and bouncing. But if temperature is lowered, the system will be able to become liquid and even solid. Such physical phenomena occur when, with decreasing temperature, molecules have so low a mean kinetic energy that they cannot any longer resist the electromagnetic interaction. They first gather in liquid state and finally get bound in solid states".

The subsequent questions are:

I. Do you think that this text suggests the following statements:

Statement 1: At a given time during the liquefaction, mean kinetic energy of a molecule of gas is larger than mean kinetic energy of a molecule of

2. L.Viennot, 1989, all levels of teaching, Paris N=20, Milan N=25, training in didactics.

liquid (liquid and vapor are in thermal equilibrium at the time considered).
Statement 2: At a given time during the liquefaction, the mean distance between particles is larger in the gas than in the liquid.
II. Do you think that:

Statement 1 is	true	false	why?
Statement 2 is	true	false	why?

Among 181 students in the three first years at University, 77% think that the text suggests statement 1 and 69% think that this statement is true. The corresponding percentages for statement 2 are 80% ("the text suggests statement 2") and 85% ("statement 2 is true").

As recalled earlier in the paper, mean kinetic energy depends only, in classical thermodynamics, on temperature and is therefore the same for systems at same temperature, for instance two phases of a substance at thermal equilibrium. This is recalled by the author of this text one page further (not reproduced in the test).

In interpreting these facts, one may first notice the strong input of temporal connotations in the text: "if ... the system will be, ... they cannot resist any longer, ... first .... finally ...".

This suggested chronology superimposes on the logical chain, as follows: $T \searrow\rightarrow e_c \searrow\rightarrow$ electromagnetic interactions win $\rightarrow$ liquid state $\rightarrow$ .. $\rightarrow$- solid state.

Linear and chronological, this text seems in perfect resonance with the features characterising the "linear causal reasoning". The idea subtly induced by such a chronology is that the story begins with high temperature and gaseous state and finishes with low kinetical energy and liquid state, no room being left to envisage simultaneously gaseous and liquid states at same temperature. All these students, however, know that at thermal equilibrium the two phases are at same temperature.

The very high percentage of students who accept statement 1 as true supports the hypothesis that they share the type of reasoning described earlier (linear causal reasoning), and seemingly encouraged by the text.

6. DISCUSSING OUR TEACHING GOALS: SOME REMARKS IN CONCLUSION

There are various points which can be discussed at length about the greater or lesser correctness of some of the excerpts quoted above. One might then ask whether comments such as : "at high altitude, there is less molecules, so pressure is lower", or "thermal motion is higher in gases than in solids", or "molecules have so low a kinetic energy that they cannot resist any longer the electromagnetic interactions..." should be banished or not.

This is not the point of interest here. Rather than discussing the correctness of these statements, let us just note that such *"soft qualitative reasonings"* gloss over the difficulties of multivariable reasoning, that this

is, most of the time, not pointed out, and that the contradictions which may arise from a careless extension of these simple and evocative ex planations are not confronted. These facts deserve attention and bring us back to the crucial question: what are our teaching goals,
- to make students familiar with particulate, or atomic structure of matter, or with other ideas or phenomena;
- or to teach them how to reason in a coherent way (in particular with several variables), and to show them the limits of each level of explanation?

This alternative is put in a provocative way. In fact, in the constructivist view so widely shared now among researchers in science education, familiarity with ideas is of no real value if a personal construction of concepts by child en has not occurred. In other words, there cannot be any conceptual learning without any reasoning. So we ca drop our first alternative and replace it by this question:
- which kind of reasoning do we aim at for our pupils or students when introducing such and such ideas or phenomena? This question is double faced:
- which (available) kind of reasoning will help them to grasp new concepts (for example in an inductive progression)
- which kind of reasoning will they learn?

It seems to us that it is important to be extremely careful in such a specification. For instance, inductive procedures aimed at introducing particulate ideas raise the following questions:
which experiments in physics, and *according to which logic*, support a particulate model rather than a continuous one? A classical theory, hydrodynamics, accounts for changes of volume and flows with a continuous model which, of course, respects all the necessary conservations, dynamical ones included. Not to speak of quantum mechanics which is also continuous with respect to space. Many teachers are not aware of this lack of evidence. In a workshop in a recent international conference[3], participants were asked which experiment(s), among the following, were the most appropriate to introduce particulate ideas:
- change of state
- dissolution
- difference in color for different concentrations
- expansion and compression of a gas
- diffusion
- non additivity of volume in the mixing of water and alcohol;

about a third of participants chose expansion and compression of a gas. So, there is a danger of pseudo demonstrations.

This would support the choice made, for example, by Meheut and al.

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3. IIIrd International Conference on Research in Science and Mathematic Education, Santiago de Compostela, 1989, Workshop by E. Enciso, J.A. Llorens and F. Sebadra.

(1987), i.e. introduce ex cathedra the basis of a particulate model, then ask children to work on it.

This however leads us to ask the question: what kind of work, should the students be involved in the learning activity? A work about conservation of mass and number of particles through changes of volume or changes of state has been proposed by several authors (for instance Meheut e.a.), a goal very appropriate to pave the way for learning the basis of chemistry. Then the difficulty is again to specify what kind of work it is possible to do in a consistent way. One may envisage activities of a descriptive type: children or students have to describe in terms of a particulate model changes of volume or changes of state. This may also be consistent with goals which emphasise explanations. The difficulties stressed in this paper suggest that, at any level of teaching, only two attitudes are self-consistent.

- One is to be extremely careful about the degree of "explanation" actually expected, and to specify what cannot be accounted for in the frame of the proposed description. Thus, for instance, the following levels of understanding may be envisaged: "Gases can change their volume to a large extent but (without the beginning of a kinetic theory) we cannot explain why they resist a compression before molecules are in contact".

"Solids expand when heated (contract when cooled), we cannot (yet) explain why. Knowing that thermal motion increases (decreases) in such a case is not enough to explain why this makes the solid expand. Indeed, the particles might vibrate more intensely, and stay around the same place without drifting (a matter of anharmonicity of the potential of interaction between particles!)."[4]

"At equilibrium between, say, liquid and gas, thermal motion (mean kinetic energy) is the same in the two phases, and we cannot (yet) explain this surprising thing. In other words, we cannot explain why, with the same thermal motion, some molecules are linked to each other and others are free. We cannot explain why thermal motion keeps the same during the change of state. We know indeed that an input of heat is used to break the links between particles in the liquid. But we do not know why it is used only for this and not also to increase thermal motion."

- Another possible teaching strategy is to work with some "*soft*" explanations, but without hiding the dangers of a careless extension of such explanations to other cases. For instance, to work with the following ideas:

"At an altitude, there are fewer molecules, therefore pressure is lower"... adding: "this reasoning works only if the molecules have (more or less, admittedly) the same velocity in the two compared cases.

"When a tyre is heated up, it becomes harder because the molecules have a larger mean speed"... adding "this reasoning works only if the same

4. It happens even that they vibrate more intensely being closer to each other, for instance when ice melts and the resulting liquid water is subsequently heated.

number of molecules is still in the same volume" (obviously not the case since the tyre is harder, but an approximate constancy of volume may be invoked).

This kind of *harder qualitative reasoning* may be considered too demanding, but it is the price to pay for consistency in dealing with such phenomena.

Of course, if one is interested in fostering the multivariable reasoning for itself, rather than illustrate phenomena connected with particulate structure of matter, one may choose simpler examples first. The area of a rectangle is a function of two variables: hard qualitative reasoning may be trained on similar simple examples.

However such teaching goals, linked with general features of reasoning, are not much in favour at the moment, overshadowed as they are by more content-specific objectives. However, one point at least must be made clearly: in our students, linear causal reasoning will be the most likely outcome of teaching which never confronts it.

It seems therefore that we cannot avoid a debate about our teaching goals, which should more explicitely consider the kinds of reasoning we expect our pupils or students to learn.

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PASSING FROM ONE MODEL TO ANOTHER: WHICH STRATEGY?

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1. INTRODUCTION

Models used in physics are of a limited nature and their use is ephemeral. They are limited in that each of them is applied to a limited experimental field. Their use is ephemeral in as much as they have to be modified and adapted to apply to another experimental field.

We must, therefore, expect the students to be in contact with not one particulate model of matter throughout their school-time but several. The object of my work is to give a contribution to the study of passing from one model to another by students aged from 11 to 13.

In this study, we call a model a didactic transposition of scientific models. Two such models, particulate models, have been presented to students during the didactic sequences we shall now describe. They are descriptive models of matter including invariants (discontinuous elements of matter) and relations between these invariants, essentially distances, speeds, etc... Each of these two models is adapted to a given series of macroscopic observations which constitute its empirical reference.

But we also call a model some of the interpretations that the children give of the experiments. These are at a macroscopic level. The invariants are not so poor if the children are able to recognize the conservation of physical dimensions such as quantity, and to describe it with physical dimensions such as volume, mass, temperature, and even pressure in the case of the gaseous state. Such descriptions can be considered as a first modeling of matter, going further than the simple description of invisible air, for instance. These childish models are more or less elaborate, according to the relationships children are able to bring into play. We know that they have less difficulties to establish relationships for an unique system in time, than for several systems, time being fixed. (Séré, 1985).

So we shall describe children passing through three successive models of matter. Their main characteristics are the following.

1. The first is their own *macroscopic model*, fitting some experiments, showing that gases exert actions.
2. The second is a *particulate model* fitting the same experiments.
3. The third is a *particulate model* fitting some chemical reactions between gases and solids. It has some points in common with the preceeding. It also has important differences.

The object of the study is to see how children acquire the different models they are proposed, how they can pass from one to the other, how they can understand the hypothetical character of the model. We shall have two points of view:
- a cognitive point of view, we shall study the intellectual operations involved in the reconstructions the children carry out;
- a psychological point of view, through the cognitive conflict which appears when a model shows itself deficient, incapable of accounting for new experiments.

These results will allow to specify the functions of particulate models in physics teaching.

2. DESCRIPTION OF THE DIDACTIC SEQUENCES

The results which follow come from the observation of two didactic sequences, outside the context of a class, intended for a group of about 10 children aged from 11 to 13. They were offered experimental activities, during which they knew they could express themselves freely. The teacher was capable of adapting the later sessions to the interpretations and questions expressed. Very often, a first very spontaneous interpretation was asked for: "Describe.... explain... " The teacher also put questions in the form of experimental problems. For example, having distributed little boxes on which an elastic membrane was stretched (fig.1), he asked: "How can you inflate this little membrane without touching it?" These problems have been constructed so that the students have the opportunity to express their representations of gases and of the actions they exert.

The series of sessions was recorded on a video-tape recorder. The tapes were transcripted. The students were interviewed individually before and after the sequences. The individual interviews were recorded and wholly transcripted as well.

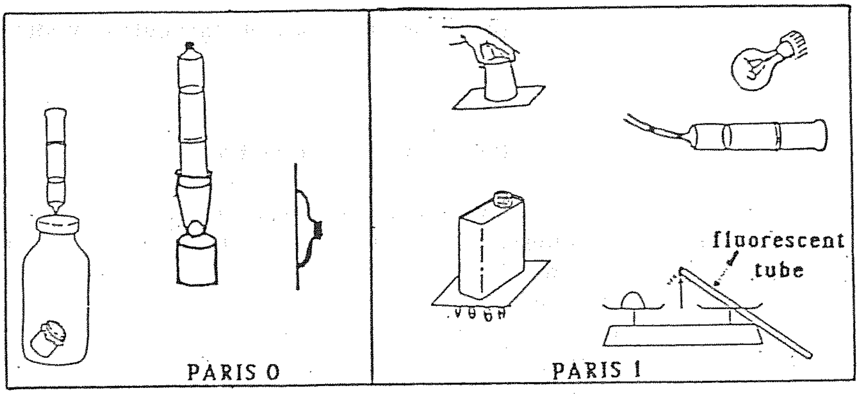
Paris experiment: the students "move" from a macroscopic model to a microscopic model[1]

The general theme was: "Physical properties of a gas, especially forces exerted by quantities of gas. Interpretation by the concept of pressure". This theme was studied on the macroscopic level during the first part of the experiment (we call this part "PARIS O"). During this first part, 7 sessions were devoted to the formation of the concepts of quantity, mass and volume of gas. We will not speak of these sessions here. We will limit ourselves to the sessions concerning the effects of gases and the formation of the concept of pressure.

The difficulties of interpretation for the students arise at the end of PARIS O. Together they specify and formulate the contradictions and

1. We thank Alain Chomat who was the teacher for the observation in Paris.

refuse the elements of interpretation which the teacher tries to give them to help them over these contradictions. Thus we decided from one week to another to give another direction to the sessions. We elaborated and gave the students a text containing an underlying particulate model providing answers to their difficulties (appendix 1). Figure 1 shows some of the experiments carried out before and after the proposal of the particulate model. The last sessions were devoted to the interpretation of other experiments with the model.



Sannois experiment: students move from one microscopic model to another[2]

SANNOIS 1

This was a duplication of PARIS 1, after a short introduction similar to PARIS 0, to complete the teaching that the students got in class on the physical properties of gases. We found similar results in this new sequence and we had no difficulty to provoke the same type of contradictions, and so to propose exactly the same reference text to the Sannois students, but in the form of a software detailing it, to help memorization, with questions, answers and explanations in the case of repeated wrong answers. There was no graphic animation.

SANNOIS 2

One year later this sequence is composed in the following way: individual interviews with each student (exactly the same ten students) to find out what he/she remembers of the SANNOIS 1 sequence.

- The first session is devoted to remind them of particulate model 1.
- The teacher presents sort of tests to differentiate apparently identical colourless gases. Gas A (O_2) brightens a small flame. Gas B (H_2) puts out the flame, making a sound (the barking of H_2). Gas C (CO_2) puts out the flame quickly. Then the children are asked to burn a piece of

2. We thank Michel Moppert who was the teacher for the observation in SANNOIS.

charcoal in gas A. After combustion, the gas is "tested" again. The students find gas C and notice the presence of drops of water. The group tries to understand what happened, with the help of model 1. They recognize that this is impossible and this constitutes the contradiction which is for us a cognitive conflict, existing between the first model and the new experiments. They make hypotheses about the differences between the "little balls" of each sort of gas.
- The teacher gives the students a text, containing a second particulate model. (The text is given in appendix 2). It is presented to the students in the form of a software.
- The students redo the same experiments and interpret them with the new model.
- The students burn sulphur in oxygen, then magnesium in carbon dioxyde, and make interpretations by means of model 2. They make drawings of these experiments.

During a final interview, there is an important verbal part (the questions concern the elements of model 2) and an experimental part (each student has to interpret an experiment about synthesis of water).

3. TRANSITION FROM THE CHILDISH MODEL TO THE PARTICULATE MODEL 1

This passage concerns the sequences PARIS 0, PARIS 1 and SANNOIS 1.

The childish model

The model each child constructs to interpret the same number of experiments is purely original. However, in these models regularities can be found from one child to another. Concerning the actions exerted by gases during different transformations, they have been studied elsewhere in detail (Séré, 1985) and summarized during this seminar by B. Anderson. We will expose them briefly as follows.

a. At constant temperature

A movement (of an elastic wall, of a syringe, piston, etc...) is always caused by another movement. The experiments are interpreted in terms of transmission of movement. For example, when air is taken out of a container containing a capsule (a little box with an elastic membrane), the students interpret:

"It's the flow of air which pushes the membrane and makes it hollow. There is only a thrust when the air arrives. It's the arrival of air that draws the membrane and gives it its round form".

The "cause-movement" and the "effect-movement" have the same direction. In the previous experiment, if the small box is turned over, with the elastic wall downwards, the students predict that the same actions as before will not change now the form of the membrane.

At equilibrium, there is no movement and, therefore, no action produced by air. In the previous experiment, when we cease to send or draw back the air, the students say that air stops pushing. Consequently, atmospheric air produces no action. Air has a pressure (as a parameter and not as a pushing force) only when it is "squeezed", that is to say when the quantity of air per unit of volume is greater than it is for atmospheric air.

b. At a temperature different from the ambient temperature

In case of a temperature increase, the hot air moves from bottom to top and is capable of moving something, of pushing. In case of a decreasing temperature, there are very few interpretations by the students: cold air is immobile, does nothing.

This modelling suits all heating experiments quite well, when the source of heat is, for practical reasons, situated under the apparatus to be heated. It is less suitable when the heating is next to the apparatus to be heated (see an experiment with this principle in fig. 1).

The link established here between force and movement is akin to models observed in experiments about mechanics by Piaget (1973) and Viennot (1977). The essential characteristic is the identification between the directions of movement and of the produced effects.

Contradictions leading to conflict

The childish model suits rather well the experiments involving air in movement. It is not surprising that it raises difficulties in experiments involving motionless air. During the seventh session of PARIS 0, the students had to interpret two of the experiments represented in fig.1: the suction pad and the piston of the syringe supporting weights.

Children could not agree on an interpretation. Some claimed that the rubber of the sucker was glued, others that it's the air inside which is compressed and resists. Nathalie gave a right interpretation in terms of pressure and nobody listened to her! Finally, the teacher gave the answer: "The air is still pushing". From this moment he was in conflict with the students who refused to believe him.

Stéphane (Paris): "I don't agree that it pushes. Air presses down on my head but not on my feet. Air can't climb up!"

Nicolas (Paris): "I say it does not push. It's there. It does not move. It stays without doing anything."

Roberto (Paris): " It's not because it touches the suction pad that it pushes it. You can touch without pushing."

Boris (Sannois): "I think that the air slips over the suction pad. It does not do anything."

Angelina (Sannois): 'Then all objects should stick to the wall if air always pushes the same way!"

The conflict has a social dimension

It did not happen exactly the same way in Paris and in Sannois. In Paris, the students have very contrasted attitudes.

Stéphane expresses himself most, insisting on getting explanations, answering the teacher very directly, refusing to let himself be convinced, finding arguments against the teacher's statements.

Nicolas seems less concerned at the beginning of the discussion. Then he takes Stéphane's side and brings extra arguments.

Alain is a "good" student who always has irrefutable arguments, often finalist (The air *must* always come back to its normal place. There *shouldn't* be a vacuum. For an object to fall, there must be air above and below). He does not like to be convinced by his peers. He is always on the teacher's side, suggesting the following argument: "Since the air touches the suction pad, it pushes it against the wall". Let's say right now that, although capable of making the model work, he always comes back to his arguments and his final interview is one of the least rich.

Roberto and Philippe are not interested in the debate, at least at the beginning. They have the typical attitude of students lost in the class, who have to adopt the observations, the reasonings and the conclusions of the leaders. Philippe keeps silent but Roberto ends up by intervening slighty on Stéphane's side. A few minutes later he accepts what the teacher says. In spite of his lack of initiative, he follows, understands and draws correct conclusions from the model offered by the teacher later on. We could notice it, for it is him who is sent to the blackboard to give new explanations of an experiment. Spontaneously he takes an arrow and changes its direction. During the last sessions, he says that "the little balls move about". Anyway, he does not go very far in the interpretations using the model, but further than Philippe, who never felt involved in the debate and than Alain and Nathalie, far more gifted than him, but feeling no need of new knowledge.

We have, it seems, in this little group, a similar situation to one of a class in which only a few students give really personal opinions. The others take the side of one or the other opinion expressed. As Mugny (1985) expresses it, it is the chance for them to exert their judgement, to discover that there are several possible opinions, to identify their own contradictions, to give themselves the means of arguing and progressing.

One characteristic of this conflict is the resistance that the students show to the suggestions of the teacher, when he gives explanations on the macroscopic level. On the other hand, they have complete confidence in him when he suggests or even "imposes" a particulate model.

Nicolas listens attentively and even before the end of the presentation of text 1, he takes a piece of paper to mimic the bombing of the particles and says: "So there will always be pressure!" Stéphane says that "like that, he understands that air pushes".

They ask questions but they totally believe in him. The questions are about: quantities ("Are there a lot? Can you have only one in a glass?"); reality of the model ("Can you see the little balls? If you put them closer?). If the teacher talks about them, and says that he has not seen them, "probably somebody else has seen them".

It was interesting to do it again in Sannois, for, there, the conflict has been totally provoked by us. It did not depend on the presence of a boy like Stéphane or Nicolas. It had a cognitive dimension in the sense that the students felt and expressed that their own model was deficient to explain the experiments under question. There was also a social dimension, because it was constructed, specified and identified by means of exchanges between students themselves and between students and teacher. The need for "something else" was formulated in progressive stages by the whole group.

The information offered by the teacher

As we said, in the session which followed the expression of contradictions producing conflicts for the students, the teacher offered them information about the particles which compose matter. The text given to the students in one form or the other (written text or software), has the following characteristics.

a. It is made *to reply to the difficulties of the students.* It tries to make them understand that in motionless air, there are particles in movement and that it is not surprising that air, even motionless, has certain effects. For the same reason, it uses a figurative vocabulary, chosen in function of what the students expressed previously and of what the teacher explained previously in vain. "The particles bombard the walls". "A quantity of air wins". "The gas which touches the walls". "Particles are firmly joined together" .
b. It contains an *underlying particulate model* of matter, for which the movement of particles and the action of air are joined. The invariants which constitute gases are the small spherical undivisible particles. The relations are the positions in space and throughout time. These relations are expressed through a description of movement of the particles, which allows students to understand that even in motionless gas there are particles in movement. The relationship between pushing forces and movement is not that of the action which results from it. There is no longer a cause-movement and an effect-movement going in the same direction, for the cause-movement is in every direction. As to the effect-movement, it can be in any direction, depending on the position of the wall itself. This relationship between action and movement is not contradictory to their own relationship. We supposed it was easier to understand. It must be noted that these particles follow the *first law of Newton*, since they go in a straight line as long as they meet "nothing" (In their commentaries, both teachers underlined that there is a vacuum between the particles). We noticed that all the students easily accepted this movement "without cause", except one: Philippe.
c. The description of *liquids and solids* in terms of particles (nothing is said of their movement) answers our need for coherence and will not stop the students from drawing the sides of the containers in a continuous line, which is a macroscopic representation.
d. The text also contains the *procedural knowledge* necessary for its use to interpret the experiments at the macroscopic level, essentially: to

explain the evolution of a system, you must take into account the different systems in interaction.

The students construct a model for themselves

Of course all the students have not acquired the same ability to interpret experiments. It would be too long to describe how we have been able to divide the students into three groups with characteristic reactions in their use of the model (Séré & Moppert, 1989). We would rather say what all children have acquired, and what appeared as causes of differentiation among the students.

Acquisitions of all students

a. Atmospheric air always produces actions. With the model, this statement is consistent with the relationship children establish between force and movement. It is this knowledge that the students, especially of Paris, defended with such intensity.
b. The action of a quantity of gas depends on the quantity per unit of volume and on temperature. At the macroscopic level, this double dependence is particularly difficult to assume. The model replaces it by dependence to a single parameter: the number of impacts per unit of surface and per unit of time. In a simple form, the model allows them to understand that the parameter depends on quantity per unit of volume and speed, i.e. temperature.

Nicolas expresses that very well when he says that: "When particles are heated, they do bang- bang- bang, instead of bang - bang - bang. But if the little balls are photographied, whether they are hot or cold, the same thing is found in a cm^3."

It can be said that there has been success of the model (power to give new interpretations) everytime that the procedural knowledge necessary is already available for the students, and also everytime the model *replaces several steps of reasoning by only one* present in students'conceptions. Consequently the causes of differentiation are the following.

a. A first one comes from the implementing of procedural knowledge. The students who give the most satisfying interpretations are able to take into account two systems, two quantities of air, and to compare the values of pressure. For instance:
   Thomas: "The object is bombarded the same on all sides, so it does not move"
   Cécile: "The strength of the balls of the balloon and the syringe are balanced"
b. A second cause of differentiation is the implication in the so-called "conflict". Nicolas, Stéphane, the leaders of the group of Paris, best understand the significance of the debate and accept the description of matter fitting their own relation force-movement. However Nicolas goes further than Stéphane, because of more powerful procedural knowledge. The students who followed the debate with a certain attention (Roberto, Angelina, Boris) come to about the same knowledge

level. They take the most important advantage of the functionning of the group. As for Alain, no doubt the "best" pupil, he has interviews before and after teaching which are very similar, without evolution. He refuses the debate, being satisfied with his finalist interpretations. He therefore practically does not evolve. It is the same for Nathalie (who unfortunately refused the last interview). She is the only one before the introduction of the model to be able to take into account outside air. Sure of herself she does not take part in the debate about the suction pad and restricts herself in the next sessions to macroscopic interpretations. In other terms she and Alain do not feel a need for the model, and do not acquire a lot from the sequence.

Arrangement of the reference text

There is a personal reconstruction by each student from deductions he makes from the reference text, and the inductions which are or are not distorsions of the model.

a. There are some *inductions from the representation of particles in motion.* At first the students do not retain the idea of bombardment. They are more interested in the homogeneous distribution of the particles as a consequence of motion. They retain the idea of bouncing among particles better than of bombarding a wall. Only progressively do they manage to use the data of the impacts on the wall. Then they enlarge the terms of motion and bombarding, given by the teacher, considerably. They bang, bash, touch each other, clash, crash, run, bump, hit, make impacts, etc. They even give justifications of the model: the particles bounce "because they are light". Pressure depends on the trajectory that a particle traces without meeting others, or on the number of impacts in a given point inside the gas.
b. There are some *distortions of the reference text.* Some come from the students who try to reconcile the model with their previous conceptions. "The little balls always push, but not much! It's as if I pushed a building. It would not make any difference !" "After a while the particles are so squashed that they will no longer be able to move and bombard almost no longer." Others come from the impossibility for the teacher to give an idea of the size of the particles, the distance between the particles and the number of particles per unit of volume.

4. TRANSITION FROM A MODEL TO ANOTHER AT A MICROSCOPIC LEVEL[3]

What mixtures of gases and combustions are for students. Contradictions causing conflict

The students of SANNOIS 1 accepted again to come, out of school-time to do physics, and this time it will be something like chemistry. Let's see first what they said about mixtures of gases.

During SANNOIS 1, we spoke of mixture of gases on one occasion: at the time the mass of air was measured using a fluorescent tube. The students spoke of "little balls inside and little balls outside". They wondered what happens when the tip of a fluorescent tube is broken. All came round to Thomas's opinion who thinks that all the little balls mix while continuing to move in the same way. So, for them, different gas particles are not differentiated and a mixture contains two types of particles with the same laws of movement.

The first session of SANNOIS 2 gives some information about the way students consider different gases and some combustions. About these, they give an important function to the flame which in fact produces very significant images in children. A flame is able of destroying, pushing, giving off gases, always with a certain violence. The analogy of consuming, breathing is used. Carbon attracts gas A and rejects gas C.

All these interpretations have been often observed and described in the literature. They are closed, not possible to falsify. So they do not generate any conflict at a macroscopic level.

The conflict

The conflict arises because experiments are not interpretable with the model: at the beginning of the experiment there was gas A in the container, after there is gas C, and the charcoal has changed visibly. The students try to imagine everything that could have changed in the gas particles. It is for us the opportunity to see how present the first model is in the students's mind. They show great ease in manipulating the elements of model 1. However, they consider mass, dimension, speed, and none of these can explain the changing of substance. One student supposes that the flame destroyed the particles of gas A. But two students remind the others that the particles are indestructible and that they can neither appear nor disappear. It's there that the contradiction lies.

The conflict here has also a social dimension

The conflictual situation is different here than in the first sequence.

a. Previously, it was a question of the failure of the macroscopic model of the students. It is now a question of the failure of the microscopic model given by the teacher.

3. This passage concerns the sequence SANNOIS 2.

b. Before, the macroscopic model of the child functioned quite well for a number of situations. Now a single fact produces a contradiction in the first model: the transformation of a gas into another, with a single direct observation, the change in the visible aspect of the piece of charcoal. Moreover, the representations of students on this problem are relatively poor.

The social dimension of the conflict comes from the fact that the teacher exploits the interventions of three pupils, to make the contradictions exist for the others. It is then felt by all the students. The debate can be interpreted as attempts to save the elements of the particulate model that they know. The silence which follows the discussion can be interpreted as perplexity due to the failure of the model. Students expect new elements from the teacher.

The model and information offered by the teacher

Again the teacher offers the students a reference text (given in appendix 2), that they can memorize with the help of a software. The characteristics of this new text are the following.

a. As the preceding one, it is conceived to adapt as well as possible to the conflict as it was expressed, and to the children's vocabulary. For example the choice was made to call particle any microscopic element of matter. In the totality of the particles we discern indivisible particles: little balls (equivalent to atoms) and others which have the movement described in the first model (equivalent of molecules). Words of everyday life are chosen: "little balls", "associations", destruction", "reorganization". Scientific terms are given in the last sentence.
b. The text contains an *underlying particulate model* which describes exclusively the transformation of substances. It explains none of the other macroscopic observations which can be made: the colour, the volume occupied, the state of the substances after the experiment (liquid state for water, gaseous state for CO_2, white powder for MgO, black powder for C). The essential difference between the two models is the descript on of the particles which have an unorganized movement: little balls in the first model, group of little balls in the second.
c. A *difference between mixture and combination* is implicitly established (these two words are not used). In the mixture of gases, the particles have movements independant of one another. As soon as we have combination, the particles associate to follow common trajectories.
d. The second model does not give a new description of movement. The way the motion depends on temperature is exactly the same; the number of impacts per unit of time is a direct function of the temperature. (the energy in the impact, as the violence of the impact, is not evoked in the reference text).
e. The experimental field of model 2 includes that of the first, since it is said that there "can" be destruction and reconstruction of the associations.

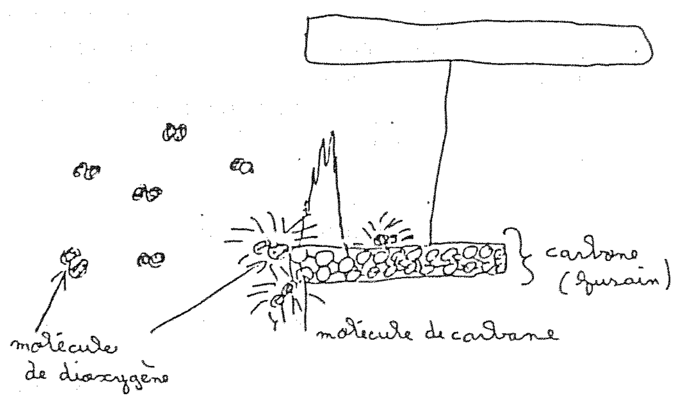
The students construct a model for themselves

The procedural knowledge which is necessary to make this second model work is simpler than for the first one. It is a matter of counting particles in groups. So the students had no difficulty for it, and constructions they make are as follows.

Inductions from descriptions of the particles and counting them

We might think that the students are a little puzzled that, from one year to the other, they get a different description of the particles which are in motion. Their faculties of adapting are very great and also they are used to seeing knowledge succeeding knowledge every year, without being able to study this succession critically. A student quickly finds the way of conciliating the two models in as much as they are contradictory. The particles must therefore be "balls with bumps" and other students repeat this image later.

All the students except one (Bruno, who says in the final interview that steam is not made of particles) can easily describe and draw gases, liquids and solids, as particulate. The solids are often represented by spherical particles which touch each other and are often surrounded by a continuous line, as is shown in fig. 2. Only the flame keeps its macroscopic aspect for all students.



Five students are capable of explaining whithout any help, that if one of the original substances is left, it is because there was too much of it and the second substance is completely used up.

Inductions from representations of motion

Let's remind that the year before, at first, the students were more ready to evoke the distribution of particles in space than movements and impacts. During SANNOIS 2, movement and impacts are immediatly present in the interpretations, and students spontaneously use very varied verbs of movement to describe the way the particles behave. All students seem capable of defining in a different way a mixture and a combination. "Combinations continue their movement in a straight line"; "Mixtures (instead of combinations) leave together"; "O and H form a pair. They are mixed" (synthesis of water).

The fact that the reactions concern the totality of gas does not seem to be a problem for the students.

Inductions from representation of impacts

The terms used to describe the impacts are varied: "The molecules percute each other, break, destroy one another, burst, set free (atoms). They break and the pieces reform"; "The atoms separate, move away, detach themselves, drop off, set themselves free, then: meet, fit together, join up, constitute (molecules), stick together, rearrange themselves, mix, associate, attach themselves, reform, go next to one another"; "The oxygen goes with the carbon"; "The oxygen takes/uses the magnesium atoms".

They also understand that there is not destruction/reorganization everytime there is impact, and there can be the same impacts as those described in the first model.

The two models are identical on one point: description of movement. In particular, when the temperature varies, it is the number of impacts per unit of time which is modified. In both models, "hotter" means "more often" (This constitutes a simplification, as L. Viennot shows in this same book). The students make an induction which enables to understand better that the reactions happen from a certain temperature. They translate *"hotter" by "more violent"*, stronger impact. "If the balls are too weak, no result..."

A student suggests that *increased pressure* also increases the number of impacts and therefore the possibilities of reaction.

About the "rules", the students try to justify them. For instance one of them says that rules are necessary, for, if not, it could be obtained "one big ball made up of all the little balls, which is impossible". In the final interview Angelina explains that we can't very well know what will join together in the reactions. *"It's a surprise"*. She admits, with the interviewer, in spite of the surprise, that all the students always find the same thing. Similar ideas are expressed by others. As for Alexander, he states that he cannot know in what proportion oxygen and hydrogen join together to give "steam".

What is left from the macroscopic representations?

We have seen that these are very poor. They give importance to the flame specially. We see that it is quite different after the expos of the model: for all the children, the flame "accelerates particles", it causes stronger and more frequent impacts. And this is expressed as much immediatly during the last sessions as during the final interviews. Even

Bruno, observing the synthesis of water, attributes this role to the flame, which, for him is also responsible for the noise produced.

We can say, therefore, that, at least provisionnaly, for these students the impacts of the particles are the main cause of the chemical reaction.

5. CONCLUSION

To conclude, we will resituate the results of this research in the total research which is carried out at LIREST on models and on activities of modelling in secondary education. We think that we always have to specify the following points:

a. *Empirical reference fields, experimental situations* have to be described. In this work, the experimental fields about which we elaborated two models were disjoint experimental fields.
b. It is necessary to specify *the scientific models of which models taught are a transposition.* The very simple models we proposed to students refer to the kinetic theory of gases, where particles follow the mechanics of Newton. Moreover we are conscious that we chose a rather poor particular description of changing temperature.
c. The type of expression used, the *signifiers*, (verbal, graphic, software), can be various and studied as so. In this work we did not try to exploit the possibilities of different signifiers. We limited ourselves to verbal signifiers with few drawings. The study of other signifiers has been done at LIRESPT for other domains (Meheut, Larcher, Chomat & Barboux, 1987; Weil-Barais & Lemeignan, 1988).
d. The *functions* of models suggested to or elaborated by the students have to be determined.
e. The *cognitive operations* proposed to the students have to be known. Induction and from what (experiment? information?), deduction, are the operations which allow a model to work.

The research of which Martine Meheut exposes a part in this same book takes another look at these questions. Her strategy was to offer students, in a class-room context, the progressive elaboration of a model whose reference field is limited to the physical transformations of matter. The students could adapt the model to new experiments by inductive types of reasoning. The strategy that we used is quite different. It offered successively to students, information on two models. This supposes successive ruptures which had to take place in students' minds. So we chose to present these *ruptures* in such a way that they are justified and that they involve the students. The recognition by a group of insufficiencies of a model, the realization of the contradictions, seemed to us favourable conditions to create a need for a new knowledge and the acquisition of it.

Although we could only carry out a case study, it showed that the students' progress was partly due to accepting conflict provoked in the group. Knowledge of students' conceptions is indispensable to stimulate such conflicts which directly involve students, to give them a collective dimension. We have shown other causes for the success or failure of the models offered. They originate in *cognitive operations* which the students have to do, in order to make them work.

Moreover, the movement of particles suggest many images to the students. They reason from movement, from "bombarding" of the walls, from impacts between particles. When this involves procedural knowledge available in childrens' minds, it allows them to get round difficulties. This happened for the following pieces of knowledge.

a. All the students learned that *atmospheric air* always exerts actions.
b. Most of them were able to characterize and to have a proper image of air, *changing its temperature*: the impacts between particles are more frequent and more violent.
c. They got images of a mixture of gases and also of a combination of two substances (the difference being that the particles involved have joined/separated trajectories). It allowed them to describe combustions in terms of chemical reactions.

These results enable us to claim that the models offered to the students, had two functions. A function of *explanation* since they allow them to give interpretations of experiments which go further than at a macroscopic level. A function of *representation* since they give a unified representation of two disjoint experimental fields concerning gases, in spite of the ruptures between the two models. It can be expected that having such an exploitable representation of gases will be of help for students.

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APPENDIX 1

Text 1 (Paris 1 and Sannois 1)

A. Any quantity of air is composed of small (invariant) particles which are spherical. These spheres are so tiny that it is impossible to see them. (There is vacuum between them).

B. Each of these spheres, although tiny, hass a mass (weight).

C. These small spheres are always in movement. We even know that they follow straight lines at high speed. When one of them impinges on another one, they bounce. Similarly, when it impinges on something (the side of a syringe, a membrane or anything in the gas), it bounces. When it does not meet anything, a small sphere goes straight on.

D. So, any object in gas is everytime "bombarded" by millions of these small spheres. And if this object can move (it is the case of a membrane) it is pushed and even shifted. If there is gas on both sides of the object, it is pushed on both sides. The side where the "bombardments" aree the most frequent, wins.

E. When the particles are more piled up, i.e. numerous per unit of volume, the "bombardments" are more frequent and the thrust is stronger.

F. When gas os heated, the particles go faster. The "bombardments" are more frequent.

G. Liquids are also composed of these particles, but they are near one to another. Solids are also composed of these particles, but they are close one to another, and they are firmly linked together.

APPENDIX 2

Text 2 (Sannois 2)

1. The small particles of which we spoke in the previous model, which moven and impinge on one another, are not really similar to spheres. They are not all identical. They can have different shapes, masses and sizes.
2. They are association of smaller (invariant) particles which are actually spherical.
3. Each association contains several small spheres (sometimes one only), identical or not, stuck together. These associations have the properties (movement, impacts ...) of which we spoke. Some associations, not all, are allowed. There are rules to explain them.
4. All gases (but also liquids and solids) are composed of these associations.
5. If associations are put together, there can be, because of impacts, destruction of the associations and reorganization of new ones different from the previous ones.
6. This process of destruction/reorganization follows rules. In particular all the spheres which compose the initial associations are in the new ones.

7. If temperature increases, the speed of the associations increases and the number of processes of destruction/reorganization increases. Besides, some associations cannot be formed at ambient temperature.
8. The tiny spheres are called *atoms*. The associations are called *molecules*. The processes of destruction/reorganization are called chemical reactions.

A SIMPLIFIED QUANTUM MODEL: A TEACHING APPROACH AND EVALUATION OF UNDERSTANDING

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1. INTRODUCTION

The general principles of our teaching approach to quantum ideas for grade 13 students (age 18-19) in upper secondary school are as follows.

1. From Bohr to Schrödinger: whereas most teachers at the moment teach Atomic Physics on the basis of Bohr's model, the Schrödinger model, within our more qualitative approach based on the notion of standing waves, allows for more and better explanations, especially in relation to chemistry, and is nearer to what scientists of today believe.
2. Reduce the mathematics involved in a Schrödinger approach. We use the analogy of standing waves to understand the basic concept of *state* (n, Ψ_n, W_n) in atoms, molecules and solids. We do not use analytic solutions of the Schrödinger equation; instead, we use the Schrödinger equation in a "semi-quantitative" way to understand how the shape of Ψ-functions depends on a potential V(x). We use the computer to calculate Ψ'' and to compute states (n, W_n, Ψ_n) with correct boundary conditions.
3. Consider chemical applications, not only interpretation questions. We test our quantum model mainly by asking what macroscopic phenomena can be explained or predicted, unlike other teaching approaches where philosophical questions about, for example, the Heisenberg uncertainty relation are more central (c.f. Fischler, et al., 1989; Wiesner, 1989). We use classical analogies (e.g. standing waves) rather than stressing a "totally new type of thinking".

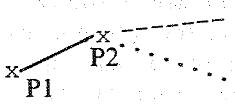
2. TEACHING APPROACH

The teaching approach consists of three parts.

1. Preparation: standing waves in classical physics (should be taught in an earlier course on "Oscillations and Waves").
   - Standing waves on a string: homogeneous; inhomogeneous (string with beads).
   - Standing waves in 1, 2 and 3 dimensions.
   - Different types of waves (abstraction sequence): waves on a string, water waves, sound waves, electromagnetic waves, probability waves.

2. Introduction of a quantum model for light and electrons (Photoelectric effect with light, Ramsauer effect with electrons, electron diffraction, double slit experiments with light and electrons).
3. The electron in atoms, molecules and solids: quantum states as standing; Ψ-waves of electrons in potential wells.
   - 3.1 The colour of dyes - electrons in square wells.
   - 3.2 The hydrogen atom - one electron in a Coulomb potential well.
   - 3.3 H_2^+ - the simplest molecule (double Coulomb potential well).
   - 3.4 Explaining Solids - many electrons in a periodic potential.

Standing waves on a string



. . . . big change in slope, big y", small λ

- - - - small change in slope, small y", big λ

Fig. 1

The generation of the y(x)-amplitude function using the computer (iteration process) is easily understandable. It also gives us a better insight into the relationship between y" and other variables (frequency, tension of the string, mass per length of the string).

The computer starts where we tell it to start (P_1). If we want to have a node at the left end of the string (x=0) we tell it to start with y(0)=0 and y'(0)=c (e.g. c=1). The computer then continues with a straight line from point P 1 to point P_2, with the slope y'=c.

At point P_2 the computer asks for information about change of slope, y". This change of slope means something very similar to the wavelength: as you can see by looking at the diagram above, a *big* change of slope, i.e. a big y", leads to an y(x)-curve with a *small* λ! That means y" $\searrow \lambda$.[1]
Now we know from experiments with homogenous strings (constant m') that:

$c = (F/m')^{\frac{1}{2}}$	c : propagation speed
	f : frequency
$\lambda = (1/f)(F/m')^{\frac{1}{2}}$	F : tension force
	m': mass per length

So it is reasonable that:

$y'' = -f^2\,(m'/F)\,y$ or $y'' \nearrow f, m', y$ and $y'' \searrow F$

This means the bigger f or m' is, the bigger y" is (big curvature!); and the bigger F, the smaller y" is (small curvature). The difference x_2-x_1 =

1. The shorthand y"$\searrow \lambda$ means: as y" increases, λ decreases.

Δx can be very small, so that after many steps like this we get a curve y(x); no straight lines are visible.

We consider standing waves on many different strings, using different thickness of strings, or beads on the string to vary m' with x, m'(x). The pictures below show, as an example, photographs of an experiment and corresponding computer simulations of a "Coulomb"-string, in which the beads have been chosen in such a way that y" is a similar function of x as for the standing Ψ-wave of an electron in a Coulomb potential. The function m'(x) in the computer-simulation has been obtained by measuring the length and mass of the beads and strings used (Niedderer, 1984).

Essentials to learn from standing waves on a string are as follows.
- Standing waves are formed in special *states*, n, which are characterized by their frequency f_n and their amplitude function $y_n(x)$.
- These states depend on the boundary conditions at the ends, e.g. node or antinode.
- We get sinusoidal y(x)-functions if the string has homogeneous mass density (and if the tension force is constant); otherwise we get a non-sinusoidal shape (y-function) for the standing wave.
- The computer can generate the y(x)-function by starting with an y- and y'-value corresponding to the boundary conditions (e.g. y=0, y'=1 for a node; y=1, y'=0 for an antinode) and changing the slope y' in accordance with the value of y", which is a function of the mass-density m', the tension force F and the frequency at every single point of the string.
- The frequency f_n is found by the computer by a systematic trial and error search for a y(x) function with the right number of nodes corresponding to n and the right boundary conditions at the ends. Students can find this correct f_n for themselves by trying one value of f, looking at the shape of y(x) and then changing the f-value to get the correct y(x)-function.

By considering standing waves in 2 and 3 dimensions, we can learn more about "quantum numbers" and the shape of nodes.

Dimension	Example	Nodes	Quantum Number	
1	string	points	n	number of nodes
2	vibrations on a tamburin	lines (e.g. circle, straight line)	n m	number of circles number of straight lines
3	standing sound waves in a glass sphere	surfaces (e.g. planes and spheres)	n m l	numbers of spheres, planes and ot er surfaces

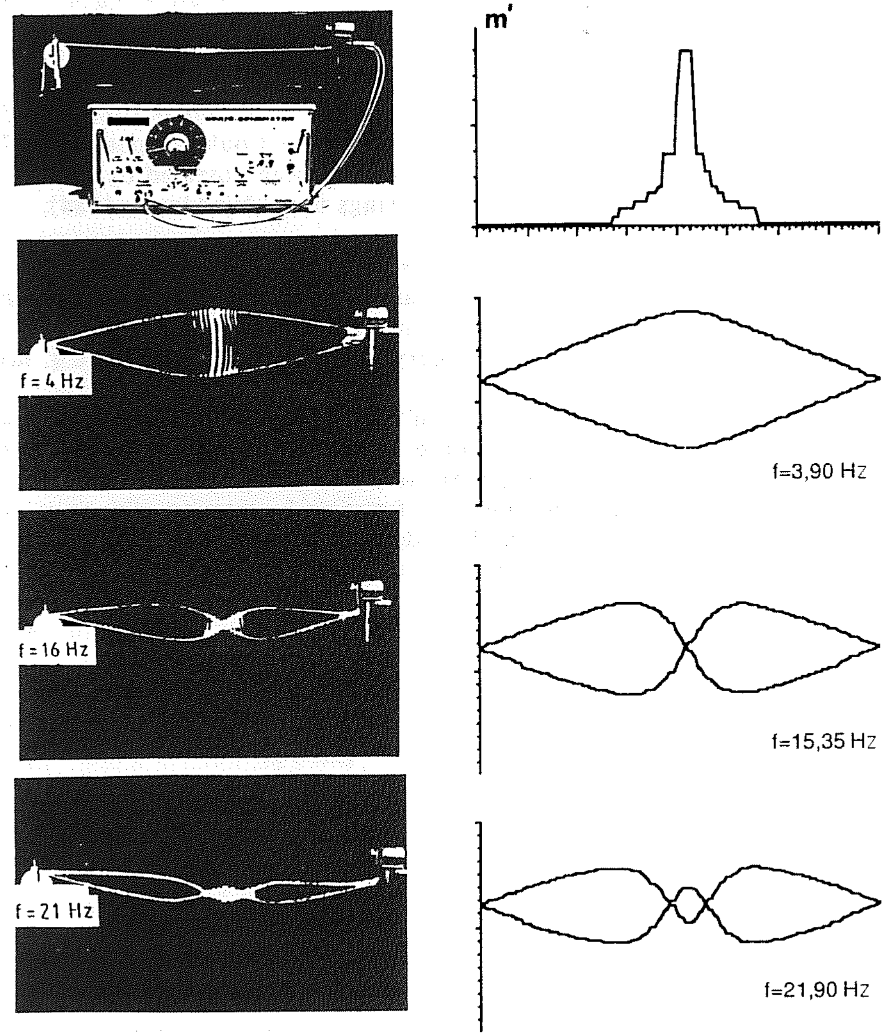


Fig. 2
Photographs of standing waves on a "Coulomb"-string.

Simulations of standing waves on a "Coulomb"-string (using a Macintosh with Stella).

The geometry of nodes for standing sound waves in a spherical glass shape is very similar to those of a Ψ-function in an H-atom! So the geometry of s-, p- and d-states in an H-atom can be understood from this analogy.

Introduction of a quantum model
The main idea in this section is to develop *one* new model Q (quantum model), through the idea that it has to integrate wave- and particle properties:

$$Q = \text{Particle} \oplus \text{Wave}$$

From our investigations and teaching experiences this seems more motivating for students than "playing around" with several different models.

So we introduce students to several experiments with light and electrons (photoelectric effect with light, Ramsauer effect and electron diffraction with electrons, double slit experiments with light and electrons). We then let them develop a model Q, as far as possible by their own discussion of interpretations of these experiments. Historical texts on interpretation of these experiments by Lenard (1902), Einstein (1905), Ramsauer (1921) and Born (1926) are part of this process.

At the moment we are discussing the following two "pictures" of the model Q in our group:

Picture 1
A quant is a particle for which we do not know anything about trajectories but only about the probability of finding it at different points. The probability density $|\Psi|^2$ is determined by a probability wave $\Psi(x)$. This corresponds to the picture below (Fig. 3) for a double slit experiment (compare also Fig. 6 for the H-atom):

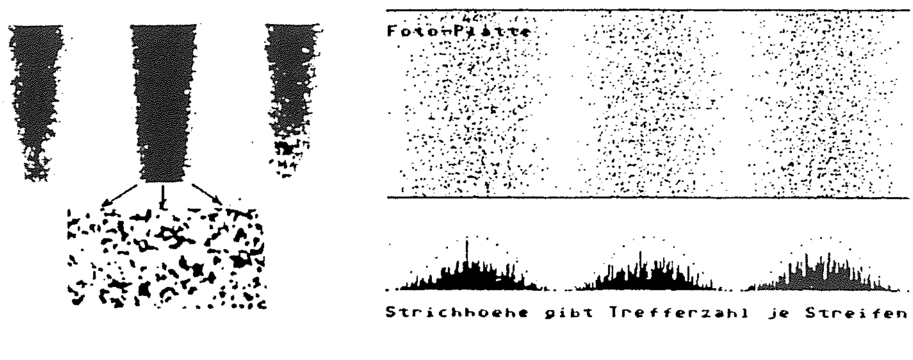
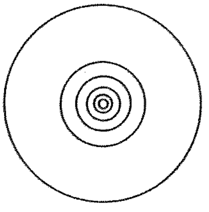


Fig. 3 Probability distribution $|\Psi|^2$ in a double slit experiment.
a. Generated in a real experiment with photons detected on a film: grain distribution on the film (two different enlargements).
b. Generated by computer simulation (Bader-Sexl, 1984).

Picture 2
A quant spreads over a certain volume determined by its $|\Psi|^2$. This is interpreted in the case of electrons as continuous charge density. If we

make measurements, however, the electron is found always as a whole at one place.

An essential part of the learning process is to see Ψ as an abstract new form of a wave - a so-called "probability" wave. This perhaps can be fostered by discussing the meaning of different waves: waves on a string, sound waves, electromagnetic waves, probability waves. We tend to call Ψ a "de Broglie field strength" in analogy to the electric and magnetic field strength of electromagnetic waves (Schecker, 1986).



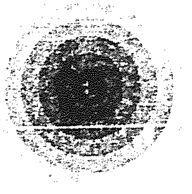


Fig. 4
Ground state of H:
a. $|\Psi|^2$-constant density lines.
b. $|\Psi|^2$-density visualized using different shades of grey.

Quantum states of electrons in atoms and molecules

In our approach these states are described as standing Ψ-waves in a potential well. This idea was originally stressed by Schrödinger (1926): "Vielmehr ergibt sich die Ganzzahligkeit auf dieselbe natürliche Art wie etwa die Ganzzahligkeit der Knotenzahl einer schwingenden Saite". (Free translation: The quantum numbers come in the same natural way as the number of nodes of a vibrating string).

The electron is restricted to a volume around the nucleus by the attractive Coulomb force which also can be described by its Coulomb potential. Any wave (in classical or quantum physics) which is restricted to a confined volume forms a *standing* wave.

So we have the following overview:

Standing Waves	
Mechanical systems	Electrons in potential wells
state n	state n
f_n	W_n
$y_n(x)$	$\Psi_n(x)$
$m'(x)$	$V(x)$
nodes	nodes
numbers n	quantum numbers n

Standing electron probability waves $\Psi_n(x)$ are developed with the help of the computer using:

- an understanding of Ψ'' and its relation to the wavelength as developed above for classical standing waves
- the Schrödinger equation in the form $\Psi'' \sim (W_n - V(x))\Psi$.

The latter equation can be derived from the de Broglie equation $p = h/\lambda$ for propagating (free) electron Ψ-waves.
With

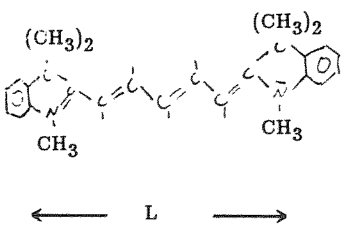
$$p^2 = 2m(W_n - V(x))$$

we get

$$k^2 \sim (W_n - V(x)).$$

For a standard standing wave we have $\Psi'' = -k^2 \Psi$, so this leads to the required equation. Our teaching aim is *not* this mathematical derivation but a qualitative understanding of the relation between the shape of the potential well (V(x)) and the shape of the resulting Ψ-function, which can be understood from Ψ'' as shown above for standing waves on a string.

Colours in Dyes
In dyes the colours are a result of quantum states of so-called Π-electrons. These Π-electrons behave like free electrons in a one dimensional potential box of length L, which can be modelled by assuming a one dimensional square well potential.



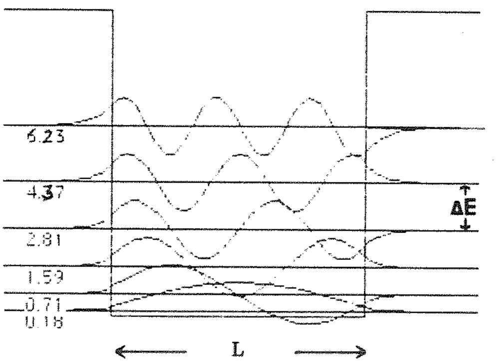


Fig. 5a. Structural formula of a cyanin molecule modelled by a one-dimensional box of length L.

b. Results of the computer simulation: Energy eigenvalues and Ψ-functions for the states with quantum numbers n = 1, 2, ..., 6 (using a Macintosh with the cT-programm "Quantum well").

In our case (1,1', 3,3,3', 3'-Hexamethyl-indo-pentamethin-cyanin-iodine) L is taken from the structure of the molecule to be 1,33 nm, and the well is assumed to be 10 eV high. There are 10 Π-electrons in this molecule. In accordance with the Pauli principle the highest occupied molecular orbital (HOMO) is the state with n=5. Light falling on to this molecule will raise the electrons to the lowest unoccupied molecular orbital (LUMO) with n=6 or to a higher unoccupied orbital. The simulation gives an energy difference of $\Delta E = E_6 - E_5 = 1{,}86$ eV corresponding to an absorption wavelength of 591 nm. We *observe* absorption with a mean value of wavelength $\lambda_o = 639$ nm.

So the microscopic model (quantum states of electrons in the potential well of the molecule) computed by a computer simulation gives us:

MICRO $\lambda = 591$ nm,

whereas observation on a macro level gives:

MACRO $\lambda = 639$ nm.

Hydrogen Atom

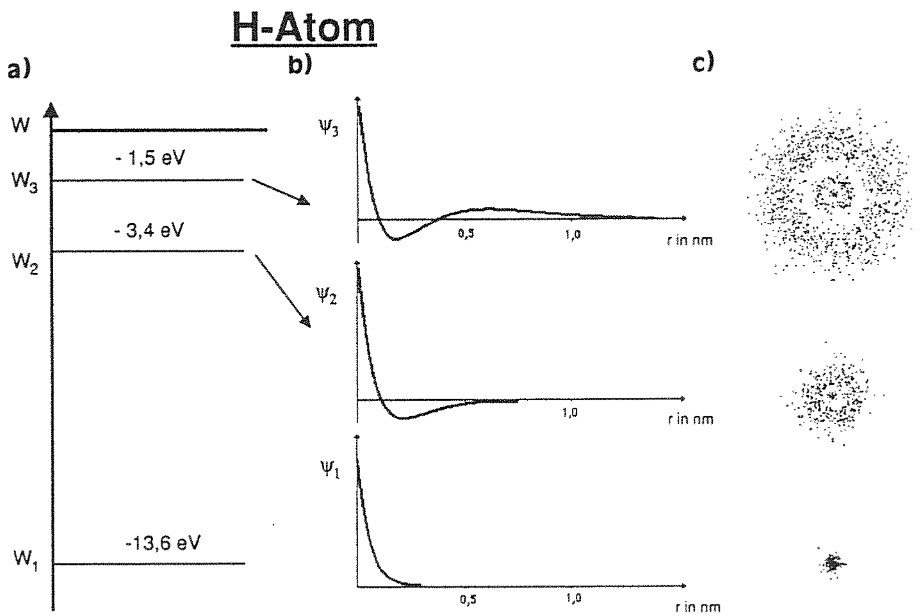


Fig. 6 Electron states for the hydrogen atom by computer simulation:
a. Energy eigenvalues;
b. $\Psi(r)$ functions;
c. Density of probability and charge.

If we look at the simplest atom, H, we have a Coulomb potential

$$V(r) = -e^2/4\pi\epsilon_0 r = -C/r \; .$$

That means that (W_n - $V(x)$) is large near the nucleus and small further away, so the curvature of Ψ-functions can be understood. With the help of the computer (using our own software by Niedderer, et. al. 1987) we get as *states* W_n and Ψ_n (see Fig. 6).

In these pictures the probability density $|\Psi|^2$ is visualized by the dot density (right hand side of the figure).

Corresponding to these results on the MICRO-level are the observations on H-spectra. For visible light we get the Balmer-series on the MACRO-level:

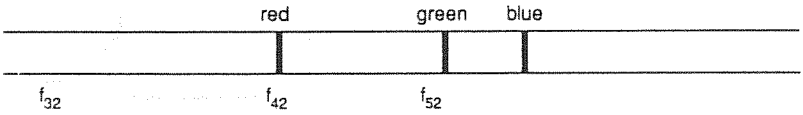


Fig. 7 Hydrogen spectrum (Balmer series).

It is well known that observed and theoretically predicted frequencies are the same to a very high accuracy! Further relations between MACRO and MICRO can be explored, for example the radius of the H-atom, which can be determined from bond lengths of molecules (measured by X-ray analysis). The measured value is between 0.030 nm and 0.037 nm and is in good agreement with the maximum value of the radial $|\Psi|^2$ distribution (0.026 nm).

H_2+-radical

This is the simplest of all molecules, consisting of two protons (two nuclei) and one electron. The simplest one-dimensional model of these two protons is a square well potential for each nucleus.

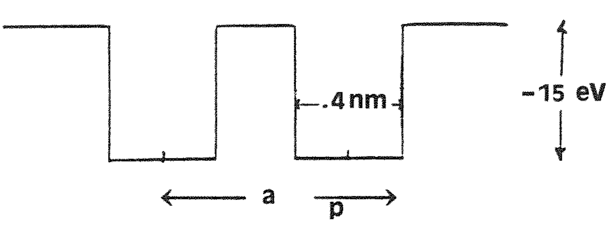


Fig. 8 Square well potential of H_2^+.

For any chosen distance a we can find the appropriate energy level W_{1B} for the first bound state (and of course for higher or non-bound states if we want). We get pictures like the following:

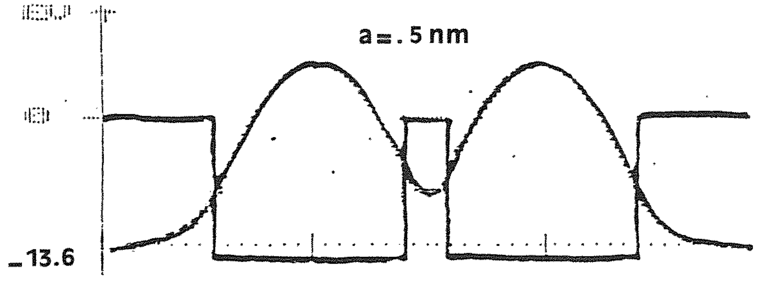


Fig. 9 Ψ-function for a = 0.5 nm.

These show a high $|\Psi|^2$ value between the two nuclei, indicating a high charge density in this region. This explains the electrostatic binding force.

If we compute the total energy W_{tot}
$W_{tot} = W_{1B} + W_{cn}$
where W_{cn} is the positive energy resulting from Coulomb repulsion of the positive nuclei, we get the following result from the MICRO model:

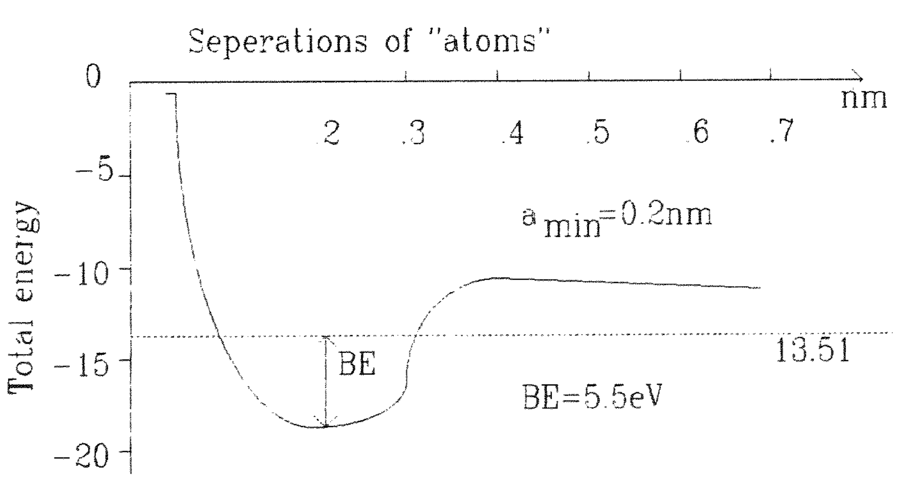


Fig. 10 Total energy E = f(a) for H_2^+.

This explains a stable distance of about 0,15 nm and a value of the so-called binding energy BE of about 5.5 eV. The observed values on the macro level are

a = 0,106 nm
BE = 2,79 eV.

For more details of computer simulations of H_2^+, see Niedderer (1987a).

3. SOME EMPIRICAL RESULTS ABOUT UNDERSTANDING AND LEARNING

In the following section we give a very short description of research results which have been published in German (Bethge, 1988). A short description in English has already been given by Niedderer (1989).

Qualitative and quantitative methods used in the investigation

1. Audio recordings of physics lessons. Four courses have been recorded and described in full, together with parts of 6 additional ones.
2. A pair-relation questionaire (PRQ). In this type of questionnaire students were asked to make statements using two given concepts, such as for instance:

wave	energy level
wave function	trajectory
trajectory	energy level
position	wave function
electron	wave
trajectory	probability

3. A questionnaire with seven "thinking type" questions.
4. Interviews with 18 students on selected statements of students from the PRQ.

A first level of description involves combining these results to try to describe general features of students' frames of thinking:

Characteristics of students' own reasoning

1. Students have a concrete picture of the atom, in terms of mechanics and the everyday life-world.
2. Students tend to use the concepts of movement and trajectory in their own explanations of properties of the atom (even if they deny them!)
3. Students tend to use the concept of energy and energy conservation in their own explanations.
4. On the other hand, students do not spontaneously request further explanations of the existence of discrete energy levels, but tend to use them as a basis for other explanations.

A second level of description is more related to students' preconceptions

1. Movement (and trajectory) are continuous; for every two points of the movement, the points between also belong to the movement, even if

they are not observed. At the beginning and at the end we have the same body, even if we have not watched it in between.
2. A trajectory is a definite and ordinary path, such as a circle or an ellipse, but not some strange zig-zag-movement.
3. The stability of an atom is the result of a balance between an attractive electric force and the activity (= force or energy!) of the movement of the electron. The electrodynamical problem of stability is not present in students' views.
4. Energy is seen as some activity or general cause which is specified in special situations (sometimes as a force, or as energy in a physical meaning or even as a kind of matter).
5. Probability is seen as some kind of inaccuracy. If you do not know something exactly, you talk about probability.

The investigation of Bethge (1988) was concerned with students' understanding, not with learning. But it was carried out using different methods (as described above) during and after ordinary teaching of atomic physics with a quantum model going beyond the Bohr model in grade 13 (age 18-19). So we think the results may be stated in the form of hypotheses about states of learning.

State 1: ("rookie")
Concepts were not enlarged or changed. The quantum states of the atom are conceived as trajectories; the model of the atom is similar to the planetary model; students hold a "strict particle view" of the electron. Probability is only an expression of inaccuracy.

State 2: ("semi-professional")
The new concepts of wave and probability have been attached to the old concepts of particle orbits and trajectories, e.g. students think of "smeared orbits". (Compare to Piaget's idea of "assimilation").

State 3: ("professional")
The new concepts are used in students' own reasoning; some problems and inconsistencies are discussed in a competent and open minded way which is to some degree comparable to the interpretation discussion in physics:
- the non-existence of trajectories is used as criterion of correct quantum mechanics;
- probability in the sense of frequency of position is used as a calculus, translating mathematical statements of the Ψ-function (e.g. $\Psi = 0$) into physical statements about the possible position of an electron (e.g. electrons cannot be here);
- the distribution of the electron in an orbital is viewed as the result of movement of the electron. The conflict with the non-existence of trajectories is noticed by students, but they cannot see any possibility of solving the problem.

From several quantitative results, especially those of the "thinking type" questions, we estimate that about 25% of students reach state 3, 40% state 2 and 35% stay in the original state 1.

Discussion

The empirical findings are perhaps a necessary start but are not very encouraging from the view point of teaching.[2] We think they point to the following consequences.

1. The approach of aiming for *one* ("best") quantum model corresponds to students' interests. It seems possible to initiate students' conceptual learning by giving them experiments and the general idea of a *new* model as some kind of synthesis between particle and wave. Then students should be given a chance to discuss their own ideas. This should be done for several important experiments: photoelectric effect, Ramsauer effect, electron diffraction, double slit experiments with light; spectra (e.g. of H-atom); absorption spectra of dyes. Discussion of this type of teaching strategy have already been published (Niedderer & Schecker et al, 1982; Niedderer, 1987b).
2. To overcome mechanical thinking about movements and trajectories, the discussion of the Heisenberg uncertainty relation (HU) should perhaps play a bigger role. So far it has sometimes even been left out of the teaching sequence to leave more time for applications in physics and chemistry.
3. The results about energy levels (accepted as a basis for further arguments) could lead to a totally different teaching approach, taking energy levels as the basic axiomatical facts.

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2. In fairness it has to be said that the teachers in Bethge's investigation were not following in detail our teaching approach described above.

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ON TEACHING AND LEARNING ABOUT ATOMS AND MOLECULES FROM A VAN HIELE POINT OF VIEW

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1. FROM MACROSCOPIC PHENOMENA TO THE NEED FOR A PARTICULATE MODEL OF A SUBSTANCE

The theme of this seminar is: "Relating macroscopic phenomena to microscopic particles, a central problem in secondary science education". We as chemists, physicists, etc., may find it evident that 'atoms', 'molecules', 'ions', 'electrons' are all physical entities, and thus formulate as a central teaching or educational problem: "Which macroscopic phenomena make it *plausible* to speak of microscopic particles?"

We might ask ourselves whether this idea of a particle as a physical reality is self-evidently the starting point to learners. If we listen to our pupils, might it be possible that their reactions, in many cases called "misconceptions", have to be understood as "Your particles are not in the world around us. Tell me what your world is, so that we can see your particles too"?. In other words: "Which things around us do you see as evidence for your particles"? So should the central problem of secondary science education not rather be in what sense macroscopic phenomena have to become problematic to the pupils? If so, we have to ask ourselves: "Which macroscopic phenomena make it *necessary* to speak of microscopic particles?"

If we try to answer this question for the pupils, I expect many of us will meet a gulf of 'ununderstandableness'[2] when using chemical or physical terminology. In fact, I consider the so called misconceptions as a consequense of prematurely overbridging a gulf of 'ununderstandableness'. I think most of us are ignorant as to which phenomena make the concept

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1. I thank the people who have helped me with the translation and also gave their criticism on my preliminary paper. Especially I want to mention B. Harris, K. Klaassen, W. Kaper, R. Millar and H. van Sprang.

2. The Dutch expression we found useful is "kloof van onverstaanbaarheid" or "elkaar-niet-kunnen-verstaan". Because "onverstaanbaarheid" has no English equivalent, I put the translation "ununderstandableness" in quotation marks. Sometimes I have translated the Dutch word "kloof" by "gap" (in which I named the "misunderstanding-one-another" as a "communication gap"). In other places (Ten Voorde, 1987) I used the word "cleft". Now I am convinced that "gulf" is the best didactic term. The translation of "elkaar-niet-kunnen-verstaan" by "it is impossible to understand each other" is then also expressed in "gulf of 'ununderstandableness'".

of particles necessary. I also faced this problem and I came to the conclusion that there is a difference between the language which is useful for speaking about substances etc. as macroscopic phenomena and that which is useful for speaking in terms of atoms and molecules. In the latter case one is speaking about the structure of the substance.

I rather see the function of the 'particle' concept, along the lines of the following quotation taken from Roest (1963) as "to describe the specific events objectively, independently of the person of the observer, in such a way that they (the events) are reproducible under similar circumstances and to consider them (the events) as a logical consequence of generally holding rules". The pupils should experience the need to search for such rules.

To answer the second question above, we then have to answer questions such as:

a. which macroscopic phenomena ("specific events") need to become 'direct experience' for the pupils;
b. what language should we develop in chemistry education so that pupils might develop "general holding rules" which enable them to consider those phenomena as a logical consequence of these rules?

In order to prevent prematurely overbridging a gulf of 'ununderstandableness' I have changed my framework of education into one which enables pupils to express their experiences with phenomena in their own words (§2). I have found the Van Hiele (1984;1986) levels (§3) useful to operationalize questions a en b as points of view for developing a teaching structure. I describe in section 4 the "level-scheme" developed in my research in chemistry education. Next I will give a verbalization of this scheme from a point of view to develop science-concepts (§5). By including the quantitative aspects of chemical reactions, the 'chemical atom' concept can be developed by the pupils (§6), but I expect an overlap of both the physical and chemical context to be necessary for developing the particulate structure of a substance (§7).

2. EDUCATIONAL FRAMEWORKS

In science education I perceive two frameworks which embody different emphases: one in which the "transfer of subject matter" is emphasised and another in which developing the scientific method is emphasised. Over the last forty years we can observe a shift from the first to the second framework. Since the 1950s, training in the scientific method has received more attention. The 'introductory concept of teaching' can be seen as common to both frameworks (§2.1). An attempt to leave both these frameworks behind me is outlined in §2.2.

2.1 The introductory concept of teaching

First I give a few personal anecdotes which describe some of my experiences in education at secondary and tertiary level. After that I will interpret these personal accounts.

Experiences with maths education as a pupil.
In the first two years of my secondary education (1946; 11-12 years old) it was self-evident the maths teacher talked within the area of geometry in terms of a logically-consistent coherence between axioms and propositions (e.g. we started with: a line as an infinite number of dots). The teacher defined the properties of geometrical figures. As a pupil I learned them by heart. I became constantly confused because I was not able to reason in the geometrical context and I didn't see the significance of this kind of reasoning. Of course I learned to reproduce the proof that, for example, two triangles are congruent, but it didn't come out of a need of mine for such coherence in reasoning.

Experiences with chemistry education as a pupil (1948).
Not only my mathematics education at that time can be characterised in that way, but also my experiences in chemistry and physics education (1948-51). If I had to do calculations in these subjects or to give an explanation of a phenomenon I had problems. In a way I learned to master these kinds of tasks. In this way, and because I was good in reproducing chemical facts, such as those of organic chemistry, I got high marks for chemistry.

Experiences as a chemistry student.
During my study (1951-59) I felt that this was not the way to become a chemist. Sometimes I had the feeling that I had some insight (e.g. in a physical chemistry topic or in the freshman course laboratory work). Nevertheless I mastered a lot of the content of my study through learning by heart, because the matter represented in the university chemistry language also wasn't mine. How do you learn a language with which you are not confident?

Experiences as a chemistry teacher (1955-63).
When I started teaching chemistry I used the same textbook from which I had learned my chemical facts in the secondary school. After introducing a new pupil book in which the particle idea was more emphasised as a starting point for concept development in the course, I got on the one hand more resistance from the pupils in the first chemistry year, but on the other hand when they were promoted to the second and the third year of the chemistry course the pupils were better prepared for the examinations.

In spite of the latter I became (about 1960) increasingly dissatisfied with the kinds of teaching results (or learning results) I was obtaining, even when introducing more practical work. I was not able to recognise these results as insights into chemistry.

It is common in this style of chemistry teaching to introduce molecules, atoms and ions before chemical symbols and formulae are learned. After the pupils have learned to describe chemical reactions using molecular-formulae, they then have to unlearn this attitude as soon as they have to describe reactions in electrolytic-solutions, because they now have to use ionic-formulae. Although many pupils accept this change in approach after a long period of training, the second description remains for many of them a learned (on the authority of the teacher) but unreal manner of describing. Repeatedly they make the mistake of representing e.g. ascending hydrogen-gas, coming into being in a reaction of a metal and an acidic solution, as H^+ in stead of H_2.

Interpretation

The statements in textbooks, mostly results of scientific research, have to be learned because the experts are speaking. The learner has to take on these facts without knowing how these results have come into being. This way of learning occurs and is emphasised by the teacher even when the learner does not have experience of the matter which is spoken about. The teacher takes the intelligibility of his technical language for granted. The knowledge that is transferred with the language is usually called "material" (as in "the material for the exam") or "subject matter" or sometimes "factual knowledge" or briefly "facts". Teaching and learning are considered in this framework as continuous processes of transfer of subject matter from the learned to the learner.

Teaching in the sense of training in the scientific method of thinking has been given greater emphasis since the second world war. The method to be transferred should reflect the way scientists work and the experimental approach of scientists has often been seen by teachers as self-evident to pupils. From his point of view the teacher considers the pupil as being qua *intention* a chemist, physicist, biologist, mathematician,....The teacher and the curriculum developer should be aware that the approach of a pupil (who has to learn the chemical subject and method) can not be considered as identical to the approach of a scientist (chemist). This difference of *intention* causes a gulf of 'ununderstandableness' which causes the pupil to reproduce the words of the teacher and of the textbook without the freedom to choose the context which the pupils find most useful. I therefore call such a situation *training*.

By aiming at insight one increasingly has the experience that such a goal is not being achieved because it demands that the pupils must change. That concept of teaching aims at individual pupils who are supposed to gain knowledge specified by the teacher or to behave like the teachers' image of a chemist. The pupils and the teacher do not have equal rights in such teaching situations because the teacher is considered an expert who is conveying the truth. Therefore, I speak of the *introductory concept of teaching* when education is directed at such goals, formulated by such an expert. I am still learning from a number of my students in chemistry of the problems which have been caused for them by education in this framework.

2.2 The 'exodus' concept of teaching and learning[3]
My experience with the gulf of 'ununderstandableness' in my own chemistry course, which I described in 2.1, was the reason for my wish to design a new concept of chemistry education. I had to abandon the introductory concept of teaching, but where could one go? I had to choose new perspectives from which to structure the teaching situation in my classroom, but how could I find them? In the following personal account I verbalize some of the experiences which were influential in changing my framework of chemistry education.

Unblocking our 'verbalitical' knowledge and originating empirical learning
I met (1963) four other chemistry teachers having a similar dissatisfaction with their chemistry teaching as I had. We met two (chemistry) educators who had designed a chemistry course based upon the principle of "direct experience" (Roest, 1963), upon the discourse as a model for the structure of the teaching situation (De Miranda, 1962) and upon the Van Hiele levels (1957). This design has been used as an organiser for the chemical and educational learning processes in our working group.

When this working group began we discussed with each other the answers to the different tasks in that course design and the sequence of the tasks in it. It surprised me that by working on such tasks it seemed to be possible to come to describe reactions in electrolytic solutions with the help of element symbols (verbalized as: "changed element"), without first introducing 'particles'. This description of a reaction is related to phenomena perceived when electrolytic solutions are added to each other.

Teaching problems, talked about in §2.1, seem to be avoidable. Pupils get a lot of experiences with chemical phenomena and they learn names and a symbolic language which is related to their experiences. Now it is no longer necessary to introduce ions prematurely to describe such reactions, but on the contrary the ion-concept will be prepared by such descriptions. This meaning of empirical introduction to chemistry became significant to me, as a way to prepare insight into the particulate structure of matter.

In this course we have tried to help pupils to learn (similar to what we did) an empirical terminology which is related as closely as possible to their perceived properties (e.g. names for substances like "burned mag-

3. I can verbalize the opposite of the teaching concept "inleiden" by "uitleiden" in the Dutch language. It seems to me that "introductory concept of teaching" is the English equivalent of "inleidend onderwijzen", but I cannot find the English equivalent of my expression "uitleidend onderwijzen". The " 'exodus' concept of teaching" seems to me the most suitable translation.

nesium"). Most chemical names (magnesium oxide) are then no longer useful because they are embedded in a chemical theory.

The tasks were so formulated that they obliged us to think about issues raised by the use of words like 'substance' or 'substance-property' and to ask ourselves: what do I mean by using the word 'substance'? This way of drawing our attention was not only new to me, but so, too, was the fact that we needed to talk with each other about such questions and were able to get an answer in the group.

Now we are thrown back to giving names to substances based on what we can perceive by ourselves and what our pupils can perceive too. But is the given name (by us or by the pupils themselves) consistent with regard to learning chemistry in an empirical way? Or do we make pronouncements which are not justifiable in chemistry? For example, we found it empirically consistent to name 'sodium hydroxide' as 'sodium oxide-hydrate'. Although this name is in accordance with the way it is prepared by sodium oxide and water, it is not in agreement with the method of preparing it by vaporising caustic soda-solution. As chemists we thought that sodium hydroxide would be better, because sodium hydroxide solution contains hydroxide-ions. But experiments didn't give us confirmation and it became clear to us that the name 'hydroxide' was based on reasoning with a particulate model.

This kind of experience is important, because in designing an empirical introduction to chemistry we were not supported by our own chemistry schooling and because we came to question chemistry from our educational problem posing.

Interpretation

The structure of a teaching or learning situation like that outlined above can be described as follows.

People participate in a discourse in which they indicate the matter represented by their use of words for verbalizing their own experiences with chemical events. Misunderstanding each other or understanding only a half of something needs a discourse to come to a common understanding. It is possible to discuss a common matter when our perceptions are our guide. This means that the participants develop a mutually understandable language by which the common matter will be represented. In other words: the handling and speaking about chemical events become a structure.

All participants in the discourse have equal rights and they jointly determine the further course of events, the development of the language and the matter which should be represented by it. Analogous to our learning processes, the pupils should be able to contribute their verbalized experiences in doing something with, for example, substances. The teacher is then no longer an expert who purveys the truth but (s)he is a learner along with the pupils. Therefore I characterise this teaching situation by naming the teacher a more experienced learner and the pupils less experienced learners (more briefly called: *longer learner* and *shorter* *learner* respectively) with respect to chemistry. Together they develop a chemical knowledge and by reflecting on this process the longer learner may get insight into a *didactic*[4] *structure* of chemistry.

3. SOME CHARACTERISTICS OF THE VAN HIELE LEVEL SCHEME AS A DIDACTIC STRUCTURE FOR MATHEMATICS EDUCATION

Van Hiele's scheme of levels in learning was a reaction to a period in mathematics teaching which could also be characterised by the introductory concept of teaching, namely one in which the aim was to learn how to prove a proposition by a logical deduction from axioms. Many teachers and textbook writers were convinced that this way of learning was the best for learning mathematics. They also consider the pupil as "being qua intention a mathematician" in other words they consider the way of thinking of a mathematician as the organiser of education in mathematics or in mathematics learning.

Van Hiele and his late wife (Van Hiele-Geldof) developed (1957) their concepts of levels to design a teaching situation that enables the learners to obtain insight into the questions (problems) of geometry, arithmetic and algebra (Fuys, 1984). This also means that at the end of such a learning process the learners may be able to formulate, for example geometrical, problems and want to search for solutions.

Van Hiele spoke of geometrical, arithmetical or algebraïc concepts if the so called level 2 was achieved in one of these three subjects. In other words, learners are then "qua intention a mathematician", i.e. the learners are acting and discovering within a geometrical, arithmetical, algebraïc context. But learners only come to a need for a logically-consistent use of terms in proving a statement or solving a problem after they have first attained another level, level 1.

These Van Hiele level transfers can be made clear as follows. The right-of-way-sign, when you are driving on a major road on the continent, will

4. If the language which is spoken (by the teacher and by the pupil) in relation to the matter (about which they speak) is the subject of research, than I use the word "didactic" to characterise the framework of that research. I call a concept development in a course which is based on such research a "didactic structure". Therefore I count for example the expression "descriptive level" to a didactic terminology. The need for a similar distinction in this term to the more general term "educational" I also found in the articles of Lybeck (1988). The following didactic terms have already been used in an analysis of transcripts published in Ten Voorde (1979): group, didactical research, language field, direct experience, descriptive terms, raising of a level, relation, descriptive net of relations, analysis, subject change (in favour of a descriptive level), theoretical level.

in daily life speech not be called a square but, like the rhombus on a playing-card, it will be called a diamond. The words 'square' and 'diamond' point to different figures in daily speech and the use of these words is in accordance with the needs of daily life. This is the langugage that people are familiar with and in which they understand each other. There is no need to compare a square with a diamond and to conclude that they both may also be called 'square' if you look at definite properties. In these circumstances learners can succesfully be asked to fold an arbitrary sheet of paper and then to fold a second time so that the two parts of the first crease cover each other. If you then cut off the so folded paper between the two creases and unfold the paper you will get a 'diamond'. You can do it with different pieces of paper and still you get a diamond. Each of these different diamonds has four 'equal' sides, the creases are at right angles to each other and bisect each other. In one of these diamonds the creases are equal in length and the sides are at right angles to each other; this one may be called 'a square', when you see one side, rather than the corner, as the base.

So acting and talking in our daily life speech about the results of our actions is characterised by being tied down to visual observation: a diamond is not a square and vice versa. In this context attention to forms of figures has been selected and such a context is called *ground level* or visual level (level 0). This formation of context is not called a level transfer, because no qualitatively different kind of reasoning has emerged.

Operating with figures at this level the learners still call ◇ a diamond and not a rhombus. At the ground level, learners get experiences by working (operating, ...) with things, figures, folding paper. Because the language of the ground level is in the words of daily life speech and the meaning of the words or the *matter*[5] represented by them is tied to the situation, we call this knowledge *direct experience*.

The next level in the geometrical context, i.e. level 1, comes into being when the properties of the figures hold the attention more and more; this means they are related to each other instead of depending on direct handling and seeing. If these properties become characteristic of the figures called 'rhombus', 'square' or 'diamond', then the learner is able to reason about when a 'diamond' can sometimes be called a 'square'. The *term* 'square' no longer represents a figure that is tied to a specific

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5. I translated the Dutch expression "zaak", in the German language "Sache", by "matter". In Ten Voorde (1979) I used the word "subject" instead, as follows: "Analysing this misunderstanding, we first observe that teacher and pupils can use the same words (e.g. "copper"), but they may denote different things. The point at issue in such a conversation is different for the teacher and the pupils. Such a point at issue I will refer to as the subject. From a didactic point of view therefore it will be worthwhile to distinguish 'subject for the pupil' from 'subject for the teacher'".

situation as in the ground level, but is a symbol for a bundle of properties. By studying patterns of tiles (e.g. tile-pictures; tiled-floors), the meanings of words like 'angle', 'line', 'straight angle', 'right angle', 'triangle' also become no longer tied to the situation; these words become terms in an argument such as saying, for example, the angles of a triangle form a straight angle (180°). Such an argument may be paraphrased as follows: the angles of a triangle form a straight angle and this angle is 180^0, so the triangle has the property that its angles together add to 180^0. In addition this property of a triangle, which is called a *relation*, is not visual, but becomes a reality in such an argument.

A learner in this way gains a *structure of possibilities of handling* figures, numbers, forms of things. This structure is represented in the terminology used to verbalize *generalised experiences* as *rules* (e.g. 2 and 3 together is 5 in arithmetic; or in geometry, the angles of a triangle form a straight angle). The meaning of the words, i.e. *terms* or 'concepts', used in pupils' reasoning is consistent with their chosen point of view (a number as a cardinal number; a straight angle) which allows generalised experience to become possible through discourse. The quality of these arguments and this method of operating characterise the attainment of level 1, the *descriptive level.*

By the transition from the descriptive to the *theoretical level* (level 2) in the context of geometry, learners show the intention to prove that the sum of the angles of each triangle *must* be equal to 180°. In the arithmetic context they *want* to reason consequentially why a+b = b+a. A didactic structure to form the geometrical context means, according to the Van Hiele levels, a period of drawing attention which is followed by two level transitions.

4. THE LEVEL SCHEME FOR CONCEPT DEVELOPMENT IN THE EMPIRICAL CONTEXT OF CHEMISTRY

Instead of drawing attention to the forms of objects only, one can also pay attention to the size, magnitude, weight of objects and to the material that the objects are made of, only, or in relation to each other. By starting in this way, an empirical context of chemistry can be formed which prepares the learners to understand particles as a model for describing the structure of matter. This context formation will now be described.

As in the Van Hiele level scheme for geometry, we found it useful to have a similar didactic structure: a period of attention selection (§4.1), a transition from ground level to descriptive level (§4.2) and then to a theoretical level (§4.3), in which the pupils are able to explain chemical reactions as a conservation of elements.

4.1 A period of attention selection

A discussion about things encountered in daily life can be kept going notwithstanding the misunderstandings which arise. The colloquial language which is used is characterized by words with a multifarious significance. The variety of experiences finds expression in this richness of significances.

If the difference of opinion about the significance of a word leads to an annoying not-understanding-each-other, it nevertheless may appear that certain word combinations have become common property while others have not. I call these word combinations *language fields*. By giving attention to such language fields and by seeking for useful ones in the discussion, it is possible to come to understand one another again.

As well as language fields in which the name of the material draws attention to a specific object, there are also word combinations in which the name of the material identifies a specific substance, or thing or composed thing. By choosing the specific language field the teacher (longer learner) is able to indicate the context in which substances will be named. In this way, the somewhat self-evident, and therefore global, use of words in common language can evolve into a careful selection of words, in order to name things in a technical context (for example: "made of" versus "made from" in combination with a name of a material like "copper").

4.2 From ground level to descriptive level

After the technical context has been chosen in a group, an ordering of the multitude of materials will be possible by naming the individual materials on the basis of differences and resemblances which can be experienced by the sense-organs (sugar is white; candy is colourless; both taste sweet).

The question "Do we have the same substance?" may lead to a yes-no situation. After it has become clear that the naming of a substance property depends on the way the material is looked at, some freedom is experienced in the choice of the point of view for naming individual substances. This can be done according to the heterogeneous material (white is a property of sugar) or to the homogeneous object (colourless is a property of sugar) depending on whether or not 'shorter learners' are looking for interfaces in the material.

So an analysis leads to a transition from a visually perceived matter to a non-visually perceptible matter (according to 'sugar' in "sugar is colourless" in which "sugar" represents an object considered as homogeneous). And this analysis also leads to a disciplined use of names (e.g. 'charcoal', 'papercoal', 'sugarcoal' represent different materials, but all substance properties, such as black and combustible are the same and can be represented by the name 'carbon'). This means that words of common language (substance, material, sugar, ...) are included as technical terms in the living use of language. The name of an individual substance is no longer an expression tied to a situation, but is founded by reasoning from a chosen point of view, for example paying attention only to those properties of a homogeneous object which do not change while changing the size, magnitude or weight of the object, and calling these *substance properties*.

The matter represented by the *individual substance* concept can no longer be visually perceived. As the observation changes with the change in argument, the meaning of a 'macroscopic phenomenon' changes too or in other words: the matter about one speaks changes.

A learner has thus become attentive to the term substance as a bundle of substance properties, i.e. the properties 'colourless', 'sweet', 'density' are related to each other and this relation is then represented in the name according to the individual substance concept[6]. The name 'sugar' is a symbol for this relation. Thereafter it is possible to continue the discussion about the use of words and leading to a general exposition or *analysis*. At this point a new freedom is obtained, namely to choose that relation to distinguish the substance concept from the material concept. The learner leaves the ground level with respect to a specific theme in the discourse. Still the context, formed by selecting attention followed by a transition to the descriptive level, is characterised by 'conservation of substance'. But the pupils will now be able to have a free orientation within the framework of "conservation of substance", because within it they are going to dispose of a *descriptive network of relations* of generalized experiences.

In that framework they search for causal explanations for the changes observed.

The discourse[7] of a group of pupils after adding pieces of tin to liquid bromine

The bubbling of the liquid is called "boiling". The boiling is possible because of the heat that comes into existence by the "reaction to each other" of tin and bromine [To the reader:

6. The expression "substance" is understandable and useful in the daily speech, but also in the chemical jargon. In the second case we have to understand "substance", "substances", "individual substance" "properties of substance" in a chemical context. The chemical terms are not useful to chemists to evoke a didactic context to them. In such cases in which a chemist speaks of "substances" I will use the expression therefore of the "individual substance concept" in the didactic context. In analogy I use the following expressions: "particle concept", "chemical element concept", "substance concept".

7. The accounts in §4.2 and 4.3 are descriptions of a discourse of a group of pupils. These descriptions are related to the transcripts of those discourses as published in my thesis (1977). The process described in these accounts of §4.2. is as good as possible put into words which were also used by the pupils themselves in that discourse. I hope that in this way these descriptions evoke a groundlevel in a didactic context. This demonstrative character of the description points to a tied down teaching situation. In the discourse described in the first account of §4.2. the teacher is also participating. The transcript has partly been published in Ten Voorde (1989).

> *just as water "boils" when slowly put into concentrated sulphuric acid]. This also means the brown gas is called bromine-vapour. The colourless solution is called a solution of tin-bromine, because the tin foil disappears completely (compare: sugar-water). This doesn't mean "tin" (sugar) has disappeared. There arises, however, a new problem for the pupils: the brown colour has gone. After a lengthy discussion they conclude "bromine" has gone. When the liquid is cooled they get a white solid mass, that melts in the palm of the hand. These are neither properties of tin nor of bromine, so the colourless liquid must be a new substance. But then 'reacting to each other' means bromine and tin disappear together while another substance appears. This ability to disappear or to appear can be seen as a new property of a substance. Because the white solid mass has a melting point the colourless liquid is called 'one substance' (named: tin-bromine) and no longer tin-bromine-solution.*

As long as a 'longer learner' establishes that 'shorter learners' do not yet have dispose of an adequate descriptive network of relations, (s)he may try to speak to them in the context they are used to. In this way they can construct a common network of relations (line: 1-9).

If a new point of view "the brown colour has gone" (line: 10) is not in keeping with the 'correct' description given by the 'shorter learners' themselves (line: 5-10), then questions can arise about the connection between the disappearance of the individual substances by an analysis of their naming of these connections (line: 12-14). Now the separate visually statable changes (e.g. of a colour) are no longer involved, but the 'correct description' of the connection between them in accordance with a new point of view, 'the disappearance and coming into being of individual substances' (line: 14-20).

The abandoning of the trustworthy reference framework 'conservation of substance'(Ten Voorde 1979, p.315, 316) brings insecurity to the learners, because the self-evident use of words is increasingly brought under discussion and because the shorter learners still lack a language in which the new matter can be expressed. This *language need* may express itself in a negative description of the phenomenon (line: 13, 14) and by finding it impossibile to describe it in a positive sense. The final description is possible when the new point of view for a new substance concept is made clear (see line 14: "a new substance").

If the learner names the disappearing of individual materials in a liquid then the disappearing of a 'substance property' is not only new and strange but also does not fit with the thought scheme in which such an event might be described as a coherent totality. However this is still in accordance with "change of a substance" (line: 7-11). Dissatisfaction with the insufficiency of their analysis creates the need to find a relation as a new point of view from which to speak about a material as a substance.

The choice of the relation 'may disappear or appear' as the substance property enables the learner to make a description (a new substance appears) which correlates with the agreements that have already been made.

As soon as a change of substance properties has acquired significance in this new sense, then the reactions described as chemical events become relations in a new descriptive network. In this case the disappearance of a substance implies also the coming into being of another substance. This substance concept I call a *chemical substance* concept.

Language fields belonging to the ground level of chemistry ("tin-bromine solution") are then no longer useful for describing the events correctly (line: 18-20). The freedom to choose a new point of view includes the need to stick ("one substance named tin-bromine and no tin-bromine solution") to this choice, i.e. a disciplined choice. Demands are made on the use of the words in which the observed phenomena can be described, *correct description*. In this new context a change in the properties of a material is a signal for a reaction as the disappearing and appearing of substances. This perception is not possible on the ground level.

Discourse[8] *of a group of pupils about the reaction of magnesium with steam*

This chemical reaction is a new one for the group. It addresses the problem of how to describe a reaction using names of substances. The group has an experience of water vapour disappearing while oxyhydrogen (called "bang-gas" in Dutch). appears. Also it knows that magnesium reacts with oxygen and a white powder comes into being. At first there is a little bang at the end of the tube before you get a flame. Now a problem arises when a pupil argues that, if the reaction in the tube is called 'burning of magnesium', there must be oxygen gas in the tube. Where does it come from? A difference of opinion divides the group into the subgroups A and B.

A: this group says oxygen has come into the tube from outside (with boiling water and together with the steam).

B: this group has the opinion there can be no oxygen gas in the tube, except at the moment the reaction is initiated. After this oxygen has been used, the magnesium continues to burn however.

The little bang and the flame at the end of the tube are considered signals of "bang-gas" or "hydrogen" (they use both names). This is being linked up to their experience with "bang

8. A part of the transcript of a discourse of a group of pupils, lasting for about thirty minutes (during which the teacher didn't participate), has been published and analysed in Ten Voorde, 1979 (315-319).

gas" appearing when water vapour is heated very strongly. This reaction may be made possible by the heat developed by the burning magnesium. This reaction of water vapour is called "decomposing" by group B only. According to this point of view another substance besides hydrogen should come into being and this substance could be oxygen. Group A objects to this because, as they say, when both hydrogen and oxygen are in the tube, the tube should explode. Both groups do not come to an agreement and give a different reaction scheme.

When A asks B to prove its opinion than B is not able to do so. But it is still convinced of its own correct reasoning.

On a descriptive level a shorter learner getting acquainted with new chemical phenomena will look for characteristics in order to be able to describe observations using the names of individual chemical substances. This is possible with the help of a testing of experiences in such a new situation against the experiences that have already been put into words (line: 3-10). By orientation in such relations a 'shorter learner' will try to describe phenomena by linking arguments to provide causal coherence (line: 10-15). The need for a correct description, and the experience that such a connecting argument cannot be brought about, forces the learner to seek for a new point of orientation (line: 12-25).

An extension of the already available network of relations is made possible not only by testing the phenomena against earlier named experiences, but also by consequently trying with existing arrangements to arrive at a linking argument. But in that case the quality of reasoning is given priority (line: 23-26) over a description in terms of material- or substance properties (line: 26-28). Now the separate, named relations constitute the terms of the argument. In this case demands are made on the language of the descriptive network of relations; there should be no deviation from this use of such terms. With this sort of *free orientation* about connections between relations, shorter learners will be able to use a more extended descriptive network of relations; the learner has experienced a leap further from the visual world.

If the other participants (group A) in the discourse are not yet able to make this leap then the longer learner (group B which realises a transfer of level) will experience a gulf of 'ununderstandebleness' because the longer learner is convinced of the correctness of the description but cannot justify it. And the linking reasoning cannot be understood, even after repetition, by those who are still not searching for characteristics of the descriptions of connections (group A).

Group A's asking for an explanation may be understood by group B as a request for a justification of the choice of the point of view implied by the use of such a term. But if the longer learner is not yet able to do this (line: 30, 31), (s)he will experience a dissatisfaction about not yet being able to explain the connections. The intuitive conjecture about the possibility of such an explanation strengthens the need for such a justification; the attainment of the descriptive level also includes the preparation for the next transition of level.

4.3 From descriptive to theoretical level

Learners may fill up their descriptive level by formulating empirical rules related to kinds of individual reactions and individual substances and naming them accordingly. The more learners experience that a certain individual substance disappears and/or appears in many different reactions, the more the question arises, at descriptive level, how to describe correctly a reaction with names as symbols for the individual chemical substances. This leads the learners to suspect that a connection between the different, individual chemical substances may be possible, and the need increases to describe the connections between those relations. But in that case, for example to describe the reaction of steam and magnesium, the name 'steam' as a symbol for the substance 'water' represents at least two possibilities of reaction: a substance which is formed by disappearing of hydrogen and oxygen and which disappeares if hydrogen and oxygen are formed. In that case the name 'water' cannot be the same symbol in the description of the reaction of steam and magnesium (group A in §4.2), unless 'water' has become a name for a node in the network of those three reactions (group B).

Learners may find a useful point of vie as soon as they have arranged the great number of different individual reactions into a few groups of types of reactions by looking at the number of substances concerned in the reactions (such as: one substance gives two substances; two give one, two give two,... or if a letter is used as a symbol for an individual subtance: P->Q+R resp. Q+R->P resp. P+U-> V+Q). Group B constructs in that way a coordinating structure by using the type of reaction as an argument in reasoning. Learners may then experience some individual substances (such as Q and R) as the endpoint of a series of decomposing reactions and/or as a startingpoint of a series of compounding reactions perceived by themselves. The name "oxygen" functions as a symbol in this coordinating structure for group B.

When the descriptive level fills up with more networks of relations the increase of the number of substance names, functioning as nodes in these networks, will cause, in growing measure, a feeling of dissatisfaction. Learners will become sensitive to the restrictions of their use of words as terms in describing and naming the individual chemical substances and the individual reactions. If the letters Q and R have become a symbol for an individual chemical substance which is also experienced as an endpoint in a series of reactions of the type 1->2, then the combination of the letters Q and R, like QR, as a symbol for the chemical substance P is in accordance with their own experiences, when QR means: if P disappears then Q and R jointly appear and the reverse. But if we use such a formula as an argument to say that by jointly disappearing of P and U, Q and V will jointly appear, then one does not experience the use of the formula QR as a correct description. The pair of the letters Q and R is not used in that case as a possibility of jointly appearing of the substances Q and R (as experienced by the learners), but Q and R are used now as a symbol for the impossibility of a reaction like Q→W+Z. If this will be an argument then it cannot be one at a descriptive level since one has not perceived such a property, but one has to choose a point of view to create a structure in the possibilities for describing the experiences with chemical phenomena. One makes then a transition to, what I have called, a theoretical level. Perhaps group B (line 30, 31 in §4.2) suspects by intuition an in-consistency in using the name "oxygen" in such a reaction and experiences a lack of arguments for the required reasoning.

Such a description of a reaction becomes logically consistent if the meaning of a term like "hydrogen" is changed into that of a chemical element, as is possible in the transition to the theoretical level. When shorter learners choose to consider two properties of a chemical substance as one property, a consistent classification and naming of chemical substances proves possible (Ten Voorde,1977). Such a new property may be "appearing in a 2→1 reaction and disappearing in a 1→2 reaction" or "appearing in a 1→2 reaction and disappearing in a 2→1 reaction".

In fact such a relation between two chemical properties is the matter which is represented by that one, new property. The learner on a descriptive level has no objection to naming the chemical substances which have these combinations of two chemical properties as "composed substance" and "composing substance" respectively. The following discourse was the result of such a classification problem.

The discourse of a group of pupils about consistent descriptive possibilities

The group of pupils continues its discourse as a result of the following two questions in their textbook.
"Is the classification of substances into 'compounded substances' and 'compounding substances' an unambiguous one? Is it permissible to call the being-a-compounded-substance or the being-a-compounding-substance a property of chemical substance?"

The group understands "ambiguous" in the sense of having two meanings, namely "compounded" as "originated out of two substances" or "you can decompose it into these two substances". A property of chemical substance is, by agreement in this group, understood to be the disposition of a specific substance to a specific reaction. On this ground it is said that "being-compounded" may not be called a property of chemical substance. So the group is able to formulate its opinion that these two properties together should not be called a property of chemical substance. This reasoning is in accordance with the agreed-upon concept of chemical substance.

This group pronounces that a "compounding substance" is a material in a compounding reaction but "never" *a product of a compounding reaction.*

Thereafter this group pronounces the relationship verbalised by "compounded substance" as "consists of". It elucidates this, not by pronouncing the relationship between (or the "ambiguity" of) the two substance properties with "or" (in the sense of "this one or the other one"), but by emphasising the ambiguity with:

..ór *you can decompose it in ...* ór *it has been originated from different substances".*

In this case "consists of" implies not only "compounded from" but also evidently "decomposing in".

Another group raises objections to this group's opinion about its interpretation of "ambiguous" (or... or..). This group answers that for "compounding substances", the same "ambiguity" also exists: "it can also be product of a reaction and *it can be material for a reaction".*

Further on in the discourse, this group pronounces either property is sufficient to speak of "being compounding" or "being compounded". And these two properties are called in that case "chemical property". This group considers it impermissible to call such a property a chemical substance property. It is able to express this property in the name of a substance. The "being compounding" is represented by a single name (e.g. hydrogen or oxygen) and the "being compounded" in the composition of these names (e.g. hydrogen-oxygen or oxygen-hydrogen). In other words: the name of the substance functions as a model for "being compounded" or "being compounding".

After classifying according to that criterion, by conducting many new experiments, the pupils may become aware of the logical inconsistency in the naming of the two classes of substances (line: 1-7). The learners become conscious of the restrictions imposed by the tied down character of the terminology used. At such a moment they feel a need for a different quality of reasoning, because they want to say something about *all* substances, all reactions,..... ("never" in line: 20). This means in our case they have to answer the question: is our classification unambiguous or not? In this case they have to choose a new point of view to express themselves unambiguously. This means that each of the two pairs of two chemical substance properties must be 'one property, no more nor less', but this is no longer a reasoning at descriptive level and that property may not be called a substance property.

One of these two new properties may be named as compounded and the other one as composing. But then the combinations of the words "compounded" or "composing" with "substance" like "compounded substance" and "composing substance" are no longer a consistent language field (line: 22-48). To come to an agreement the learners have to contrast sharply these two, new properties with chemical substance properties in the language of the descriptive level.

By taking such a standpoint (line: 30, 31) the learners set themselves the task of bringing a structure to their use of terminology at the descriptive level. They develop at this stage an argument at the theoretical level. The transition to the theoretical level also means that they gain a structure in the possibilities attainable to them for describing (line: 38-48). Their building-up principle may be useful and may be called: *chemical element*. This implies the general rule of conservation of chemical elements. Instead of describing a chemical reaction as the disappearance of substance(s) and the appearance of other substances, a chemical reaction may also be considered as a rearrangement of elements and described according to it.

The 'oxygen'-problem at the descriptive level for describing the reaction of magnesium and steam can be solved by such a building-up principle and not only in this reaction but in *all* reactions. Names for individual substances are constructed from names of the chemical elements as components, or, as is usual in chemistry, the formula as a symbol for the substance is constructed using letters as symbols for the elements.

5. THE VAN HIELE LEVEL-SCHEME AS A DIDACTIC STRUCTURE FOR SCIENCE EDUCATION

With respect to our use of the term 'level' for describing the articulation of the teaching situation, structured according to a lasting discourse in which pupils and teacher take part on the basis of their own experiences with phenomena, I found a similar level-structure in context-formation as the Van Hiele's did for mathematics education. Van Hiele, De Miranda and Ten Voorde concluded in their lasting, didactic discourse (Vogelezang, 1988):

- To name their levels in the same way, namely as: ground, or visual level, descriptive level and theoretical level and that these three levels presuppose each other. This means that a 'subject' context has been formed by a period of attention selection, in which a ground level is originated, followed by a level transition to a descriptive level and then by a transition to a theoretical level.
- If participants in a discourse use the distinguishable languages of two levels, then a gulf of 'ununderstandableness' exists. The difference in meaning of a word at distinguishable levels cannot be elucidated by an explanation, but has to be discovered by the learners' own activities. So as to make a transition from one to the next level, a different concept of teaching from the one called "introductory" (§2.1) is required (see: §2.2).

A teacher cannot teach a level transition nor show it to his pupils. The pupils decide to take part in such a level transition when they need it. But as long as a group of pupils (learners) uses words appropriate to a lower level whilst another group uses the combinations appropriate to a higher level, the first group will not understand the second group. It looks as if each group is speaking its own language. In such a case one perceives a *gulf of ununderstandableness* within the class. The explanation of the second group to the first has no direct result. Nevertheless this discontinuity in understanding may disappear after a specific teaching period as the first group may also learn the language of the second group.

In other words: the teacher does not teach a term or an argument at a descriptive level but guides the learning process by asking questions, searching for words, giving tasks according to the phase that the level transition has reached. The first phase in a level transition may be the dissatisfaction with the use of combinations of words (language fields). This is, at the first level transition the tied down character of the meaning of words, and at the second one, the inconsistency in the use of words. This dissatisfaction with the relation of words to each other requires an analysis of the use of words and then a choice of the point of view needed for exploring new relations and for selecting common useful words to describe these relations in a different language. At the descriptive level being in accordance with the chosen point of view forms the criterion for consequential reasoning. To take away the dissatisfaction with logical inconsistency in the use of words, a standpoint or principle has to be chosen in order to justify, in a consistent argument, the choice of the point of view by which a descriptive level has already been achieved.

The formation of such a context means a change in the nature of the teaching situation as regards the way pupils and teacher operate with the matter and the language they want to speak. In other words if we perceive the teaching situation as being a lasting discourse, than the structure will vary according to the matter which is spoken about, as well as with the quality of argument used and the people who participate in the discourse.

Didactic research to other subjects of science education may test the usefulness of the terms I used here to conjecture a general didactic structure for science education.

6. HOW TO RELATE MICROSCOPIC PARTICLES TO MACROSCOPIC PHENOMENA?

The level scheme described in section 4 leads to an empirical context in chemistry in which the chemical element concept, developed in the transition to a theoretical level, functions as a model in the terms of the quotation in §1, namely that the specific events may be described independently of the person of the observer and in such a way that they are reproducible under similar circumstances and are considered as a logical consequence of generally holding rules.

During the empirical chemistry context formation the quality of reasoning in the language development is related to "macroscopic phenomena". But the way in which one speaks about the observed phenomena changes with the transitions in the level scheme. Therefore I say the matter-language relations also change according to this level scheme. The matter-language relations coming into being during the transition to a theoretical level in a chemical context may result in a quality of reasoning which is a prerequisite for a context in which atoms and molecules could be a physical reality. But is that chemical context also sufficient?

Consistent with the Van Hiele level scheme, the following questions may arise :

- can the desired particle concept be developed in the transition from the descriptive to the theoretical level of the "empirical context"?
- or do we have to develop the particle concept in another context distinguishable from the "empirical context" but prepared for by the "empirical context"?

6.1 The chemical atom

In the empirical chemistry context, as described in § 4 the term 'substance' represents at descriptive level a phenomenon which is characterised by the chemical property "being able to appear and to disappear". Each individual chemical substance is distinguished by its own bundle of specific chemical properties. The more a learner becomes acquainted with chemical reactions, the more (s)he disposes of relations in which the distinctive, individual substances, represented by a name, function as nodes in a network of these relations.

According to that substance concept, which is also used in the name for describing a chemical reaction, we may say that in a specific reaction the individual substances belong-to-each-other. This belonging-to-each-other may be named a property of such a substance and may be, qualitatively, expressed by a name for the substance. E.g. hydrogen jointly with oxygen belong to water, so "water" is called "hydrogen-oxygen".

This "belonging to" may also include quantitative aspects concerning mass and volume. During the formation of an empirical context it may be possible to formulate at the descriptive level this "belonging-to" of the quantities of each individual substance as a mass ratio or as a volume ratio. While each chemical reaction is characterised by such a mass ratio, we may say that each chemical property of an individual chemical substance is quantitatively described by such a mass ratio. And thus each individual chemical substance too.

The more the indivual chemical substance concept functions as a node in a network of relations for the learner, (s)he may become aware of a need to bring "unity" in the description of the many different mass ratios. The learner may search for a mass number as characteristic for a specific substance and also useful to describe all its chemical properties with the help of such mass numbers. The didactic structure for a way which can be followed with regard to that purpose has to be developed by didactic research.

Some research has been done in the last ten years. It has been found possible to develop the theme "belonging to" starting with mass and volume of an object via the density of a substance to the mass ratio of the individual substances in a chemical reaction.

By focussing on the mass numbers of "simple substances" (like Q and R in §4.3) and by choosing one of them as a point of reference, e.g. hydrogen the mass number one, it proves possible to ascribe to simple substances one, or sometimes two or three such mass numbers which indicate the equivalence of those masses of the simple substances in chemical reactions.

As we saw in §4.3, pupils were able to bring about coherence in the description of substances and reactions by developing a "chemical element" concept. With this concept a chemical reaction can be seen as a rearrangement of elements. Quantifying this element concept proves possible (Vogelezang, 1990) by analysing a specific type of chemical reaction. In this type one is focused on one element in particular and this element is component of only one individual substance which disappears and of only one individual substance which appears. As e.g. P+ U $\rightarrow$ V + Q from §4.3 which may be written as QR + U $\rightarrow$ UR + Q (and P and Q are gases), if Q is the element of our special interest. Vogelezang called this type: a "one-to-one gas reaction". It is found that for a specific element the volume ratios in *all* the possible one-to-one gas-reactions form a simple scheme of whole numbers. One can understand this scheme by supposing that the mass of the element concerned is rearranged per unit volume of the gaseous substances in simple whole numbers of a comparatively "smallest massportion". Vogelezang called this "smallest massportion" a "chemical atom", in accordance with nineteenth-century chemists such as Kékulé. This "atom" represents an indivisible unity in the context of one-to-one gasreactions and does not mean an isolatable and countable particle (Vogelezang, 1990). One can thus describe the one-to-one gasreactions as a rearrangement of chemical atoms.

6.2 From 'chemical' atom to the atom as a physical reality

In the discussion (1914) between Armstrong (chemist) and Rutherford (physicist) we see a collapse of two frames of reference (Joling, 1989). In Armstrong's framework the matter represented by the term "atom" is not a corpuscle (particle) but in Rutherford's framework it is.

It seems that there is a need for a new context instead of a new level for the atom as a corpuscular-concept to be developed. If so, then the gain for the development of the 'empirical context' in chemistry is the indivisibility of 'atomic' mass as a concept. This may be a reason for choosing an entity as a new point of view and so being able to develop a structure of the atom for describing the structure of a substance. A development of a structure of the atom (with protons, neutrons and electrons) in the new context could, in terms of the Van Hiele levels, again be called a descriptive level. But then this level belongs to a context other than the one we called 'empirical chemistry'. Besides, to develop a description of the structure of the atom, one needs the concepts and principles which are developed in the 'empirical context'.

From this didactic point of view it will also be clear why a question (see: Bohr, 1913) arises concerning the stability of such a atomic structure, because the structure still describes an entity. In addition to this the network of relations for describing that entity with concepts taken from the empirical context leads to an anomaly. Bohr's choice of Planck's working-quantum as an ordering principle may be experienced again as a transition to a theoretical level. Bohr gave an account of his choice for a system of a positive nucleus and electrons as an entity, and his theory gives a possibility for explaining the stability of that structure. In other words, he had to accept an atom as a physical reality. We may also say that he brought structure to the descriptional possibilities with electrons and protons, and for that purpose he had to develop another language from the one used during the 'empirical context'.

7. CONCLUSIONS

The formation of an empirical chemical context does not necessitate the conclusion that substances have a particulate structure. Perhaps it might be a conclusion within the transition from the descriptive to the theoretical level in an empirical physics context in which the kinetic gas theory is developed. The advantage of the formation of an empirical context in both cases may be that the learners could experience the distinctive qualities of reasoning in both these phenomena.

In addition the learners may ask themselves for an image of the bodies around them as they perceive them. They gain an insight that such an image could not be the same as the things they experience on the ground level. This enables them to distinguish a description of the structure of the substance from the bodies in the visual world around them. This makes them critical of naïve physical realities taught (e.g. "a molecule is the smallest particle of a substance") and learned in the educational framework characterised by the introductory concept of teaching.

Especially in this framework of education, textbook learning leads easily to an excessive secrecy about the way in which scientists go about in getting their research results. This has the consequence that, for example by premature introduction of the particulate theory of matter, a problem posing attitude is blocked by education, and that misconceptions which arise as a result of such a premature introduction have to be unlearned. Thus the approach which I have characterised by the introductory concept of teaching is ineffective.

The growing tendency to such a *textbookification* (Joling, 1990) must be countered by progressively more problem posing instead of problem solving in science learning. In this sense science education structured according to the Van Hiele level scheme affords a perspective for teaching and learning the particulate nature of matter.

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WORKED OUT WORKING PAPERS

The second part of this volume contains the working papers, as they have been worked out after the seminar. First drafts of most papers were distributed among the participants several weeks before the seminar, sothat they could be studied.

At the seminar in parallel sessions a short presentation of the main lines was given, followed by discussion.

You may notice that, though the problem under discussion has an important common core for education in the three sciences, the particular perspective in the contributions changes gradually from biology via chemistry to physics education.

This section concludes with a report of a plenary discussion, as it took place on the last morning of the seminar

MACRO AND MICRO ABOUT THE LIVING CELL: WHICH EXPLAINS WHAT?

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1. INTRODUCTION

This paper is based on a research project about the cell concept of 9th and 10th graders (about 15 years old), who had been taught the topic. The main justification of the decision to teach this complex topic at the beginning of high school studies, or during the last year of junior high school, was the need to introduce the essential idea of the "cell as the basic unit of life". Some understanding of the functioning of the cell was assumed to be indispensable for sound understanding of the functioning of the multicellular organism. Such an understanding, in turn, is considered to be a part of the culture of the enlightened citizen, i.e. of *all* the graduates of the compulsory education system. However, we have found (Dreyfus & Jungwirth, 1988, 1989) that the attempt to teach "the cell" at that age is faced with great difficulties. These difficulties seem to stem from the very nature of the idea of "basic unit of life".

The functional unit of a complex system is in itself a "whole", which is able to maintain itself by performing some functions autonomously. These functions, in turn, are the "basic" ones of a more inclusive "whole" which performs at a higher level of organisation. The properties of the "whole" are different from those of the "units", in spite of the fact that they are directly incumbent on them. (However, a commonly found misconception is that an atom displays the properties of the substance, Novick & Nussbaum, 1978; Ben-Zvi, Eylon & Silberstein, 1986; additional examples are quoted in Eylon & Linn, 1988). In biology, pupils often confer upon the cell, or its sub-components, properties - even psychological - of the multicellular organism.

Consider the beehive: the individual bee, is the basic unit of the beehive society. Everything in the beehive is carried out by individual bees, but the behaviour of the single bee derives its meaning from its participation in the social organisation to which it belongs. The functioning of bees can therefore be observed and analysed at two levels at least: the single and the social.

However, the functional units of the *single* bee itself are its cells. *Each* of these cells performs, autonomously, some general metabolic functions, (respiration, replication, bio-syntheses, etc) which *are* actually the basic functions of the life of the bee. Other, more specific, functions are also carried out at the cellular level, such as muscle contraction, reception and transmission of stimuli by cells of the nervous systems, etc. Everything which is done by the bee is done by its cells, but the bee functions at the "whole organism" level. The single cell derives its meaning from its participation in the activity of the whole body of the single bee. We should therefore conclude this paragraph in the same way as the preceding one: the functioning of a single bee can be observed and analysed at two levels at least, the cell and the body. But, as far as pupils are concerned, it is almost impossible to observe the functioning of a cell: the cells are microscopic. They can be seen, through the lenses of a microscope, single celled organisms (protozoa) can be seen moving, ingesting food, etc. Some intracellular structures and organelles can be observed as well: contractile vacuoles can be seen while contracting, and the *presence* of a nucleus or even of chromosomes can be detected even at school by means of standard equipment and methods. But the *functions* of the cell as a basic unit of life, i.e. the basic functions of life *cannot* be directly observed. The nature of the processes which occur within the cell - its basic functions - depend on sub-microscopic structures (e.g. membranes), and on the chemical properties of sub-microscopic entities (molecules, atoms, ions) which cannot be perceived by the senses of the pupils. Such processes represent therefore complex, abstract and to some extent esoteric knowledge, which cannot be inferred from direct observation. Friedler, Amir and Tamir (1987), referring to a process, the effects of which *can be easily observed*, namely osmosis, quote from the literature (mainly from Arnold & Simpson, 1982; Johnstone & Mahmoud, 1980) many of the reasons why this concept is so difficult to teach. Some of these reasons are, in our opinion, valid to different extents for any of the basic intra-cellular metabolic processes: prerequisite concepts require knowledge of abstract and complex principles of physics and chemistry, of the particulate nature of matter, which have been found to be difficult for biology students (and definitely so for 9th or 10th grade pupils).

Furthermore, their understanding requires "a high level of reasoning as well as an understanding of the relationship between *macro- and micro-systems in phenomena* ..." (Johnstone & Mahmoud, 1980, emphasis added). Stavy and her colleagues (1987), for instance, have shown that junior high school pupils not only lacked knowledge about chemical elements, but found it even difficult to understand that the body is composed of chemical substances. To sum-up the dilemma of the biology teacher: the macro and the micro levels of organisation are *both* necessary to the understanding of the living organism. Modern biology explains many macro phenomena by means of micro, ultra-microscopic structures and processes. But the "micro" level of functioning of the organisms, i.e. the cellular and intra-cellular processes are difficult for 15 year old pupils. Many teachers and textbooks, apparently influenced by the hierarchical organisation and presentation of the scientific knowledge in scientific writings, and at the university level, tend to try to base the teaching of the observable "macro" phenomena on some "knowledge" of the esoteric "micro" structures and processes. Are such attempts sound, from a pedagogical-didactical point of view?

2. THE STATUS OF THE "MICRO" LEVEL IN THE TEACHING OF THE LIVING ORGANISM

When teachers or curriculum developers decide, in a specific case, that the micro level of representation of some scientific knowledge must be taught, is it because the micro level is a necessary condition for any meaningful learning of the macro level?

An answer in the affirmative implies the assumption of the existence of a learning hierarchy. A learning hierarchy consists (Griffiths, Kass and Cornish, 1983; Griffiths and Grant, 1985) of "superordinate-subordinate relationships between pairs of intellectual skills". Two hypotheses may serve to validate the hierarchy:

a. the inclusion hypothesis, according to which no individuals can exhibit the superordinate skill without being able to exhibit the subordinate one(s) and
b. the transfer hypothesis: learning of the subordinate skill enhances learning of the immediate superordinate one. Is any of these hypotheses truly valid, concerning the biological topics taught at the age we are referring to?

In any biological process, the *effects* of the micro level processes reveal themselves in the form of the macro observable phenomena. There are two possibilities: either the pupils, *in spite of their ignorance of the micro level*, have some intuitive or formal perception of these phenomena at the macro level, or they have no idea about the phenomena, which are entirely new to them. If the perception of the pupil is accurate, then *the micro level was not indispensable for a reasonable understanding of the phenomenon.* On the other hand, the pupils may have formed misconceptions, their precon eptions may be wrong, etc. For instance, pupils tend to perceive (rightly) the exchange of gases in breathing, and regard (misconception) respiration to be no more than that, ignoring completely the non-perceived "micro" processes of metabolic oxidation in the cell. (Stavy et al., 1987) found the same misconception in relation to photosynthesis). In such cases, they must undergo a process of conceptual change, by being supplied with new information. This information stems, allegedly, from the micro level, i.e. from the chemical or physical details of the process under study. If (second possibility) even the phenomenon at the macro level is entirely new to the pupils, that is, if it is pure "school knowledge" which has, so far, had no counterpart in the experience of the pupils, then the esoteric micro level is certainly not likely to be the most plausible base for the learning of the new concept.
Lawson (1988) says: "For students to be able to overcome prior misconceptions, ... they must be able to logically see how the evidence supports the scientific conceptions and contradicts the misconception". But 15 year old pupils are just not able to think logically about chemical or thermodynamical evidence, if only because they normally lack the necessary prerequisite knowledge.

The introduction of new knowledge in a context in which the pupils are unable to "logically see" the implications of new information, seems, according to our (Dreyfus & Jungwirth, 1989) and to others' observations, to result mainly in the formation of non-functional, non-meaningful (in an Ausubelian sense) knowledge. (By non-functional knowledge we mean that the details of such knowledge are of no consequence to the pupils (Dreyfus & Jungwirth, 1989)).

If some knowledge is supposed to confer meanings upon the understanding of biological processes, it must possess potential meaningfulness *before* the processes can be taught. To become meaningful to the pupil, such knowledge must not remain "isolated", or "inert" (a term used by Perfetto et al., 1983; Bransford et al., 1986); it must be logically connected with the existing body of knowledge of the pupil (Ausubel, 1978; Novak, 1977). But the micro level is not part of these pupils' knowledge repertoire. The micro level can therefore definitely *not* serve as a *basis* for the learning of the macro phenomena. The assumption of a hierarchy in which learning would logically flow from micro to macro, seems to be unsound, at least as far as the 9th and 10th graders we have met are concerned. But what is the alternative? After all, intracellular biochemical processes *are* the basic processes of life. Is there a way to teach 9th graders meaningfully the micro aspects of biological phenomena? Or is there a way to teach the functioning of the organism without referring to the micro level, i.e. the metabolic functions of the cell? The only pupil's body of knowledge in relation to which the micro level of biological phenomena can be logically introduced, consists of components of the corresponding macro level, or analogical macro systems, which are already to some extent familiar to the pupil. However, 9 and 10th graders, especially those who do not intend to continue the study of highschool biology, deserve to have a meaningful, if limited, glimpse into the chemical basis of life, and of its relations with the more familiar and more observable macro phenomena. The task of the educators is therefore to uncover alternative contexts, in the framework of which the micro components of life can be introduced and learned meaningfully.

3. MACRO AND MICRO IN 9TH GRADE BIOLOGY

Teaching *meaningfully* the basic functions of life, or the functioning of an organism, or of its components, means dealing continuously with relations between *structure and function*. The structure-function approach remains appropriate whether we deal with micro entities, such as the structure of enzymes, of the DNA molecule, of membranes, of intracellular organelles, or with macro-phenomena, such as the structure of the heart or of the skeleton of various animals. The need for clarification of such relations creates true *problems*. According to the American College Dictionary, a problem is "a question proposed for solution and discussion". *Biological* problems, in the context of this paper, are those which, according to our theories, are encountered by the organisms. Their solutions are structure-function systems which, according to our philosophy, have evolved by means of evolution or other phylogenetic mechanisms. The problem *of the pupil* is to find why the solution *is* a solution. The questions asked in this context are complex, and may vary according to the philosophical approach to the problem (teleological or not, for example): What is the function performed by X? What is the mechanism of X? What is the contribution of structure X to the efficacy of function Y (requiring an understanding of "efficacy" in the specific case)? What is the evolutionary advantage of structure Y? How is X adapted to Y? What is the role of ....? What is it good for? The solution will have to propose a logical, although tentative, link or web of links, between the structure and the function of the system under study. Its attainment will require some conceptual, more or less specific, knowledge, (the necessary scientific background) and some procedural knowledge (to handle questions of this type). The clarification of structure-function relations will therefore require intellectual efforts on the part of the pupils, who must grasp the nature of the problem, i.e. define the problem, (or understand someone else's definition), select relevant data, interpret them (or understand someone else's selection and interpretation of data) and suggest a solution (or understand someone else's solution) to the problem.

It could be said that teaching biology meaningfully means to teach plausible approaches to the identification and definition of new (to the learner) problems, and tentative biological solutions to plausibly defined biological problems.

The complexity of the problems the pupils are to be faced with, must obviously be adapted to the abilities and knowledge of the pupils. For 15 year old pupils, complex "ill-structured" problems will have to be "simplified into a series of small well-structured problems" (Simon, 1978), which require mainly "the information contained in the problem statement and perhaps other information stored in long term memory..." (Simon, 1978). Still, the pupils will have to be able to some extent to "link salient information", to "integrate their ideas appropriately" instead of "failing to integrate information" and "link ideas using superficial information" (Eylon & Linn, 1988). As we have shown above, the micro level does not provide the pupils with an appropriate context to do so. The problems with which 15 year old pupils have to cope when dealing with micro-entities are - to them - unusual; this is because the pupils must first become used to think on the basis of things they cannot see, and can describe only by referring to second hand and very often non-functional knowledge. How do experts respond to atypical problems? Perkins and Salomon (1989), sum-up the findings of several authors: "...because unusual problems do not yield to the most straightforward approaches, the experts also apply many general strategies. For example [they]... often:

a. resort to analogies with systems they understand better;
b. search for potential misanalogies in the analogy;

c. refer to intuitive mental models based on visual and kinesthetic intuition...". (The authors then describe further strategies, to show how the experts check "how the target system would behave...").

In our research, the pupils were found to behave in a way which may make all the difference between highly motivated and competent experts, and novices who, under some coercion, try to solve an in-school problem. They:

a. resorted (Dreyfus & Jungwirth, 1989; Dreyfus, 1989) to analogies with systems they did not always "understand better", but with which they were more familiar (as already found by other researchers, e.g. Hempels' empathic familiarity);
b. being satisfied with their familiarity with the system used in the analogy, they did *not* search for misanalogies and
c. did not try to apply the analogy to the target system, in order to see how it would function.

One example will demonstrate the type of pupil-response. When asked about the meaning of their statement "the nucleus controls the functioning of the cell", most of the pupils in our sample said "just as the brain controls the activity of the body (for details, see Dreyfus & Jungwirth, 1989). This fallacious analogy was indeed attractive. The overwhelming misanalogies did not a priori disturb the pupils, in spite of the fact that they "had", according to their teachers and to their own testimony, the micro-level "knowledge" necessary to answer the question (the genetic code, the DNA molecule in the nucleus, that the cells are made of proteins, which are chains of amino acids; enzymes are proteins; there are no nerve-connections between the nucleus and the cell; the brain is multicellular and the nucleus is less than a cell). All this knowledge remained without apparent relevance and applicability. The clues to the solution of the ill-understood problem were "inert", non-functioning, knowledge. This was not a case of momentary unawareness. Attempts to "activate" (in Bransford et al., 1986, term) pupils' alledgedly existing "knowledge", by means of various hints (in written tests or during interviews) brought about no significant improvement. Very often such pupils', analogies were based on complete ignorance, or on oversimplified knowledge of the micro-level: Since cells do specialize (a system which is familiar but appears to be only superficially understood), then, in some pupils', opinions, some of them certainly specialize in the production of energy, and this energy is later transported to the other cells of the body (superficial information leading to misconceived analogy; other examples are treated in Dreyfus, 1989). In fact, pupils had no clear idea about the nature of the problem they were dealing with. As recognized by various authors in scientific contexts (see for example Solomon, 1986), they did tend to use analogies to explain unknown phenomena ("It is as if..."). We therefore decided to use the more familiar macro level to introduce the nature of the problems, by using carefully selected analogies "with systems which the pupils" really "understand better".

4. SOME EXAMPLES

a. Let us go back to the question of the controlling of the cell by the nucleus. The pupils have learned, without details, that the building material of the body is "the proteins", that is, every living organism is built of proteins. The difference between various organisms is due to their having different proteins. The source of proteins is food, i.e. other organism that are eaten. The eater takes the proteins of the eaten and builds itself with them. Now comes the problem: if we eat beef protein, and build our body with it, how come that we are not cattle? To tackle this atypical problem, since we do not know much about proteins, we need an efficient approach. This is where the analogy intervenes: (we have described the lessons elsewhere: (Dreyfus et al., 1988) "Imagine that you have built cars with Lego parts, and you wish to build different cars with the same parts, what would you do?" The answer is in most cases immediate. The clues are much more accessible to the pupils than in the real system: "We would break the cars down and build the new cars with the parts". "And what would you need to build the new cars?" "(various answers) energy, a program (or a plan), time, etc." "The time spent on the analogical system", say Dupin and Joshua (1989), "must be economic from the teaching point of view. It must present a great structural isomorphism with the initial system". We would hesitate to use the term "structural" when referring to the structure of a problem, but the analogy was based on the only property which was common to the two systems (the initial and the analogical). Indeed it appeared to be very economic and efficient as a guide for asking intelligent "exploratory" questions about the biological system: Are the proteins made of units as the car is made of Lego parts? (Yes, they are called amino acids - a fact that very often the pupils had already learned but which had remained isolated); Is there such a program? (Yes, in the nucleus, a program which says exactly how to arrange the "structural units" the amino acids); Where does the breakdown occur? (this process is called digestion. In multicellular organisms it occurs in the digestive system); How are the parts separated from each other (specialized enzymes, in the digestive tract); How and where are they rebuilt? (specialized enzymes, in every cell, according to a program which is in the nucleus of every cell); How did the program penetrate into the nuclei of the cells (it did not; replication, division, heredity, etc.). The micro level was thus introduced as a set of answers to questions which had been asked (or at least been understood) by pupils, starting from a "system they understand better". Admittedly, not much could be said or asked at this age about the "micro level", i.e. the structures or chemical activities of the components of the system. But since the studying of the system was not based on the micro level anymore, the learners were able to acquire some robust and meaningful insights about the organism, without having first to master difficult chemical concepts.

b. Can the *size* of micro-components of the living system be grasped in some way by the learners, in spite of the fact that they are beyond human perception? Size is important, because various properties of the living systems depend on the dimensions of their "micro" components. One of the most ubiquitous biological principles is the principle of "relative surface area"; very small particles have tremendous relative surface areas. This principle and its importance are not easy to understand, and we suggest that it should, as most of the physical principles, be intuitively perceived by the pupil - before it is explained or computed. We again suggest the use of an analogical system, which the pupils can understand. "Once upon a time, a king had a very big ship, which could transport 2000 tons of merchandise. But it took a very long time to unload, in spite of the fact that the king had as many dock hands as he needed. Access to the ship was limited... So one of the ministers told him: 'Wouldn't it be more efficient to have two ships, each of them taking 1000 tons? Then the unloading time for 2000 tons would be the time needed for 1000 tons, since both boats would be unloaded simultaneously.' The king agreed and indeed everything was alright until they had the idea to build boats of 100 tons, i.e. the unloading time would be the time needed for 100 tons only. But since they had so many boats, what would they need? More wharfs, (we draw on the blackboard more branching and more ramified wharfs and then even more, smaller, ramified roads, as the load of the boats is reduced to 10, to 1 ton, to 100 kgs, etc.). From ramifications to sub ramifications, we raise the question of the efficacy of unloading. Assuming that the main problem is the efficacy of unloading (or of loading), we further reduce the size of the boats, and we establish intuitively the principle on which all the "harbours" of the body (digestive system, lungs, kidneys, etc) are based; an enormous number of very small ramifications, of blood vessels, etc. Nothing has been computed. No formal abstract formulation of the principle has been suggested. Again, the analogy was based on the common properties of both systems. A feeling of the effect of the size of microscopic elements on the efficacy of transport was developed, as a result of presenting an analogical problem at the macrolevel.

5. CONCLUSIONS

Analogies are always dangerous, because the pupils may wrongly attribute to the phenomenon (or system) under study some properties of the analogical one. The pupils who are able to distinguish clearly between analogies and misanalogies may often be regarded to be able to learn without the help of models, and the pupils who most need the models may often be the very ones who are unable to make the necessary distinctions. This is not a paper about analogies, but since they are the main tool of our suggested strategy, a few arguments concerning their educational use should be considered here.

a. Solomon (1986), remarked rightly that "common metaphorical usage is a very mixed blessing". She might say that also about our amino acids which are the "Lego parts" of the proteins. It is true and well recognised that the metaphoric language commonly and carelessly used in biology may be very misleading (enzymes "cut", etc). But in our case, the initial and the analogical systems are so extremely and obviously different, and presented as such, that there is little danger that the pupils will mix them up (no, the proteins are definitely not built of Lego parts, and the properties of the Lego parts are very obviously different from those of the amino acids, whatever these may be). The analogy was not in the physical aspect of the systems involved (analogue model, Gilbert and Osborne, 1980), but in the theoretical, general aspect of the problem concerned. The analogical features were not embedded in the physical structure of the studied system but in the nature of the problem.
b. Analogies are most dangerous, as sources of misconceptions, when the analogical system is *not* better understood than the initial one. For instance, when food in animals is compared by teachers with fuel in cars (source of energy, burning, etc), the pupils are exposed to various potential misconceptions, because they do not understand the working of the car better than that of the animal, and therefore are unable to decide where the analogy fits and where it does not. (Actually, the function of fuel in cars could just as well be "explained" by that of food in animals). However, our analogies used only systems which were well understood by the pupils. The analogical system was less complicated than the original one, (as required by Dupin and Joshua, 1989) and the components of the problem more familiar, and thus more accessible to the pupil, so that the pupil could think logically about it.
c. The most important characteristic of our strategy was that the analogies were *not* intended to serve as *explanations* of the phenomena, but as guides for the exploration of the phenomena under study. In that respect, such analogies may play an important educational role: macro- or microscopic observation, dissection etc. may uncover structures. However, even when these structures can apparently be *seen* in action, the mechanism of their functioning and the understanding of their function are not automatically understood. Various philosophers of science and, specifically for teachers, Schwab (1962) when the BSCS was introduced, claimed that observation, i.e. the selection of what we "see" as relevant details or discard as secondary, less important, side effects, etc. is not objective. It is theory laden and made "through the lenses" of subjectively selected "guiding principles", approach of the scientist (Schwab, 1962). The direct observation of the functioning heart was not sufficient to bring about the understanding of its functions. As Driver says (1987) "students will not discover them [scientific ideas] through 'asking nature'. There needs to be an input, therefore,

from the teacher or authorities to shape students' thinking..." A potential input of analogies was defined, as shown above, by Perkins and Salomon (1989); they may be important tools for the development of tentative approaches to scientific problems, especially when the concerned phenomenon tends to remain mysterious. Mysterious, for a pupil, has been well defined by Dupin and Joshua (1989), speaking of electricity, (and for some reason thinking that electricity is special in that respect): "mysterious: no acting mechanisms can be seen, only effects". To paraphrase Gilbert and Osborne (1980), the input can be seen in the fact that the analogies represented "...simplified versions" of a problem and therfore helped to "concentrate on special features", thus "stimulating investigations ...". So, even when the pupils *are* cognitively able to understand a straightforward, expository, explanation of a scientific phenomenon, the involvment of the pupils in an analogy may be a useful strategy in science education. The educational implication of the "problem centered" view of the learning of biology is not that all pupils must become highly skilled, competent, independent and original problem solvers. It rather implies that a problem centered approach is inherent in any effort to confer meanings upon biological concepts, because it supplies the logical links by which new concepts may be connected to the pupils' exisiting body of knowledge. It is also indispensable to involve the pupils in the identification of "conflict" situations (conflict between solution and data, between perception of problem and nature of solution, or between tentative different solutions, etc), and provides a context in which the pupils may assess the relevance of information and data. To sum-up: organisms function at various levels of organisation; the understanding of the functioning of organisms requires an understanding of the relations between the various levels. Scientists explain the mechanisms of several basic functions of life at the "micro" level, i.e. the biochemical, sub-microscopic processes which occur in the basic unit of life, the living cell. For many reasons, the learning of these processes is difficult, if not impossible, for 15 year old pupils. Such processes can therefore hardly serve as a basis for the understanding of the macro level (observable processes carried out by the multi celled organism). We suggest that a problem centered approach, and the use of carefully selected analogies, may assist in the inculcation of meaningful, though sometimes intuitive, conceptions about the functioning of the "basic unit of life". Such insights will be the cultural message contributed by the educational system, to those pupils and citizens, who will not study any further biology. For the others, who will continue, they will serve as a basis for the meaningful learning of more sophisticated bio-chemical and bio-physical concepts, which in turn, will later become part of the "scientific explanations" of the processes of life. This may well be a useful approach to "spiral" curricula.

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QUESTIONS ASKED IN COMMON SENSE CONTEXTS AND IN SCIENTIFIC CONTEXTS

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1. INTRODUCTION

It is now a well established fact that learners have prior knowledge, or *alternative frames of reference* (Driver & Easly, 1978) which may often come into conflict with the knowledge taught in schools. (For reviews of the field, see i.e. Driver & Erickson, 1983; Gilbert & Watts, 1983; Pfundt & Duit, 1988; Shymansky & Kyle, 1988). It is also a well documented fact that alternative frames of reference are very stable and not easily modified (see i.e. Viennot, 1979; Andersson & Kärrqvist, 1983, cf. also Beveridge, 1985; Cros, Chastrette & Fayol, 1988).

The aim of this paper is to discuss the stability of pupils' prior knowledge and to suggest how it can be understood. The thesis is put forward that questions which are demanding within pupils' frames of reference are neglected in teaching and, thus, the descriptions and explanations given in the teaching and relating to other questions lose their meaning. By drawing, *inter alia*, on some of our studies, I will propose at least a partial explanation of why attempts to alter the pupils' prior knowledge so often fail.

2. CONCEPTUAL CHANGE AND CONCEPTUAL DEVELOPMENT

In most discussions on how pupils' prior knowledge interact with the "scientific" knowledge taught in school, it is more or less tacitly understood that pupils will abandon their common sense knowledge when confronted with school knowledge. In considering the conditions for this process, one point of departure is Piaget's description of *cognitive development* (cf. Rowell & Dawson, 1983). According to this line of reasoning, pupils' *cognitive conflicts* are instrumental in their acquisition of the more potent scientific concepts. Another strategy here is to encourage social interaction between the pupils in relation to the problems actualized in the teaching (cf. i.e. Driver, 1981).

A second point of departure is the descriptions of the historical development of scientific ideas. Descriptions taken from Thomas Kuhn, Imre Lakatos and Stephen Toulmin are seen as models for the acquisition of scientific concepts. Learning is then discussed in terms of *conceptual change* (cf. Hewson, 1981; Strike & Posner, 1982; Posner, Strike, Hewson, & Gertzog, 1982; Osborne, Bell & Gilbert, 1983). In its most uncompromising form a direct parallell is considered to exist between concept development in the individual and concept development throughout the history of science (see i.e. Gilbert & Zylbersztajn, 1985; Munari, 1985; Wandersee, 1985; Thompson, 1988). Within this framework the conditions for conceptual change can be listed as follows.

1. There must be dissatisfaction with existing conceptions.
2. There must be a new conception that is intelligible.
3. Initially, the new conception must appear to be plausible.
4. It should suggest the possibility of a promising research program (after Posner et al., 1982).

Both of these approaches can be questioned as ideal paths to the acquisition of knowledge in educational settings. Cognitive development as a result of cognitive conflict and social interaction is a spontaneous process, whereas gaining knowledge in educational contexts is usually intended to be, and often is, the result of an intentional process. 'Cognitive conflict' may then mean quite different things in these two kinds of processes. In cognitive development as a spontaneous process, the cognitive conflict arises from a vast amount of experience acquired throughout a considerable period of time. In teaching, on the other hand, we must confine ourselves to a few contradictions which have to be solved within a limited period of time.

Formally, this problem is perhaps circumvented by the first condition, i.e. dissatisfaction with existing conceptions, which for the "rational mind", tacit in the description of conceptual change as a conscious and deliberate process, is a reason for abandoning previous knowledge. But the problem of contradiction and cognitive conflict remains. Pupils often apprehend counterexamples as anomalies or explain them by *ad hoc* hypotheses (Rowell & Dawson, 1983). Beveridge (1985), in a study on children's understanding of the process of evaporation, concludes that seven and eight-year-old pupils apparently hold contradictory ideas without being aware of any conflict. Or as one of our 17-olders said in an interview after doing a laboratory exercise on gelfiltration:

I: Do you think that you understood at any time what it was all about?
Ip: Well, roughly, but... thought it was the wrong way round.
I: You thought it was the wrong way round?
Ip: Mmm. I thought the little ones should come out first - but they didn't.
- - -
I: No, and so you had a problem?
Ip: No - not a problem really ... I mean, all you can do is accept facts as they are. Like when you don't really understand something but know that facts are facts. I mean, that's it. That's all there is to it.

And this is probably the rational way to behave. We do not subject our hypotheses to systematic testing because everyday events are multidetermined (Rowell & Dawson, 1983). Our spontaneous tendency is to confirm our ideas, not to falsify them; after all, our knowledge cannot be completely wrong because it has worked for us in the past (Hashweh 1986).

And, furthermore, is it really true that the theories, models and explanations given by physicists, biologists and other experts are superior to common sense knowledge in every respect? When the phycisist explains the pendulum or the principle of uniform motion, he is talking about idealized situations framed by conditions never present in real life; the pendulum swings in a vacuum and moving bodies are presupposed as being uninfluenced by any forces whatsoever. As Solomon (1983) puts it: 'It would be a poor return for our science lessons if the pupils could no longer comprehend remarks like 'wool is warm' or 'we are using up all our energy' (p.50). The biologist cites chance and causal chains to explain why there are so many species on earth and why they are so different from one another. But what does he say to a pupil who asks: *'Why then did some fish remain fish?'* Perhaps our biologist could give some kind of acceptable answer to that question too; nevertheless, science does not give us complete answers that are entirely free from contradictions or unexplained questions.

I want to try another way of looking at learners' difficulties in understanding the theories and explanations taught in school. Instead of focusing on cognitive conflict as the vehicle for cognitive development, or of seeing dissatisfaction with existing conceptions as a condition for conceptual change, I want to concentrate on the intelligibility of the conceptions presented in teaching. And here I argue that these conceptions are only intelligible within a scientific conceptual world which is separate from the pupils' common sense conceptual world. Individual concepts are embedded in a conceptual framework which give them their meaning. If the learner does not realize this or does not comprehend the essential features in this conceptual framework, the individual concepts will make no sense to him. In order to illustrate this I will draw on some examples from a study on pupils understanding of genetics in upper secondary school (the Swedish *gymnasium*).

3. THE STUDY

The study was carried out in a Swedish *gymnasium* class (11th school year). The pupils were taking the social science course which also includes studies in natural sciences. The age of the pupils was about 17. Instruction in genetics and the evolution of the species was given over a period of seven weeks and comprised about thirty lessons in all. Different kinds of data were gathered. However, here we are looking only at data from a group discussion about problems in genetics, which took place following a period of instruction (a comprehensive description of the whole study is found in Halldén, 1988b).

As part of the investigation two groups of three pupils each were assigned the task of describing how characteristics are inherited and how they undergo change over time. Both groups were given tape recorders and then were left to discuss the assigned topic in the respective groups.

They were told that in order to complete the assignment successfully, they had to arrive at as complete and detailed a description as possible and that they were to continue their discussion until consensus was achieved in the group. The account given here is based on transcriptions of the taped discussions.

The main results of the study are presented in Halldén (1988b). Here I will concentrate on the pupils' general framework and how that framework relates to the bits of information they were given in the instruction. But first I want to give a brief overall characterization of the group discussions.

4. PUPILS ON HEREDITY

Both groups found the assignment difficult, if not to say impossible to fulfill. Characteristically, in both groups there was widespread uncertainty both as to what they were expected to do and what aspects of heredity were to be included in their explanation.

Neither of the groups was able to present a coherent explanation. They did however bring up a number of points and aspects that constitute parts of an explanation. They took up cell division, genes and chromosomes. They talked about dominant and recessive traits and about mutations and DNA molecules. Each of these concepts was clarified one by one, but no attempt was made to relate them to one another so as to form a coherent whole. The descriptions and explanations the pupils proposed were not related to an overall plan as to what kind of description or explanation the problem required. The pupils did not ask themselves, either implicitly or explicitly, what constitutes an explanation of heredity and the inheritance of traits and genetic dispositions. The transition from one area to another or from one concept to another occurred through vague and general questions such as: *'Now what?'; 'Are we supposed to set up a Punnett square or something ...?'; 'What should we take up now ...?'; 'Should we take up that stuff about how cells divide ...?'.* The pupils thinking seemed to ramble from one association to another. They described individual processes, but they failed to connect these processes in such a way as to form a coherent and overall explanation of the overriding question: how are characteristics inherited? It should also be noted that the points the pupils brought up in their group discussions coincided quite well with the topics that were covered in the class examination.

The way in which the pupils did treat these concepts is indicated in the following example. One of the pupils asked the group if they should take up cell division. A second pupil responded spontaneously by saying 'IPMAT', and then all three said in unison: *'interphase, prophase, metaphase, anaphase and telephase'*, i.e. the names of the various phases in cell division. Concepts which were assumed to be needed for understanding how genes undergo cell division here seem to have been transformed into a simple memorization task.

So far then, it would appear that the pupils were able to discern the separate elements that constitute an explanation, but they did not manage to ascribe any explanatory value to these elements. There is, however, one problem, implicit in the discussion in each group, which could account for this inability. The problem concerns the question of *what* is to be explained and this, in turn, relates to the general framework for the explanation.

5. MICRO AND MACRO AS DIFFERENT CATEGORIES

In one of the groups it was stated that the hereditary dispositions for a given trait are to be found in the genes, and that genes are found in chromosomes which, in turn, are found in cells. Further, they stated that chromosomes consist of DNA molecules and then mentioned RNA and proteins in this context. The discussion then continued as follows:

P1: It's protein and stuff the body needs then.
P2: But they're not *dispositions*.
P1: No - but that's what... eh ...
P2: But then, *how* are they transmitted? Did we study that? Did we learn about that?
P1: Yeah, isn't that what we learned?
P2: But not *how*! I mean, only how it ... --- ... only about how it turns out. How ... we learned that they are inherited but not *how*... yeah.

The same difficulty is illustrated in the other group and in a similar way. The problem of how characteristics are related to genetic mechanisms is brought up at the very beginning of the discussion.

P4: It's like this. The human being has a lot of different kinds of small chromosomes where you'll find the dispositions. There're 46 of them.
P4: Aren't they found in the *genes* ... Isn't it the genes that carry the dispositions?
P5: Yeah, but aren't the genes in the chromosomes?
P4: OK. But it's the genes themselves that are the traits - aren't they!?

It appears that the pupils are questioning how everyday terms such as 'traits' and 'dispositions' are related, if at all, to biological concepts and biochemical phenomena, just as the pupils seem to be confused about how these concepts are used in genetic explanations and contexts. They seem to be questioning how the biochemical properties of the cell, or of particular parts of the cell, can be transformed into something we can label in the same way as we label characteristics of the organism, or how to translate the language used in descriptions of the cell to the language used in descriptions of the organism. The problem that is occurring to them is that 'blue-eyedness', for example, is not a characteristic of the gene or DNA molecule, it is a characterization of a particular trait of an organism. The terms used in descriptions of the gene and descriptions of the organism, respectively, belong to different categories. Thus, to identify the trait with its genetic counterpart would be an example of a *category mistake*, to borrow a term from Ryle.

So far, we notice the interesting fact that, without being aware of it, the pupils have been tackling the category problem. However, the problem turns up again, but this time in a new form. Up till now, the pupils have identified two different categories of description, but now the problem arises whether one of the categories can explain the other.

6. ON THE POSSIBILITY OF REDUCING MACRO TO MICRO

In both groups the pupils chose to discuss examples of the succession of a particular trait. In this context the concepts of dominant and recessive dispositions were brought up. In one of the groups it was decided to discuss the succession of curly hair. The following dialogue takes place a few lines further on in the transcription.

P4: 'How the baby got its curly hair!'

P5: Yeah, ... but, like, we haven't gone through that stuff. Only about how dispositions are *inherited* ... and that stuff about dominant and recessive.

P4: Dominant and recessive traits.

P5: And then we went through all that about how they're in *the cells* and lots of stuff like that.

P4 and P5: Mmmm.

P5: Actually, only in the part about inheritance, so - like, that's all we did.

P5: Yeah, exactly.

Here, the pupils considered it impossible to say anything about the transmission of traits. They had not learned anything about that; they had only learned about the genetic processes. The proposition that is implicit in their argument is that these processes are not related to the organismic level.

The other group, however, pursued the question a bit further. They took as an example the succession of colour in mice, a question which came up in a laboratory exercise on mice breeding.

P2: Is black dominant? - How do you know that, by the way?

\- - -

P1: - - - Well, I don't know *why*, but ... but you say that the wild type have to bear a capital A and a capital B. So, in some way it is dominant. - - - Well, I don't know for sure, exactly.

The pupils tried another example regarding brown and blue eyes. They stated that an offspring does not inherit everything from either one of its parents alone; instead it is '*fifty-fifty*'.

P1: And then all of them become brown-eyed.

P2: No, they don't.

P1: They don't? /pause/ Yes, they do. And then all of them will have a *disposition* for, for blue-eyedness.
P2: Right! - - - It's ... it's when you cross the *offsprings* you can see the dispositions.
(A feeling of confidence spreads throughout the group)
P1: Right.
P2: Right.
P1: That's it!
P2: Perhaps I learned something this time.

In this case the pupils arrive at a solution to the problem of how genotype relates to phenotype - you can infer the genotype from the phenotype - and in this case it is enough; their conclusion constitutes a solution to the problem of how dominance is to be discovered and the pupils were satisfied so far. Actually, it is a methodological problem, and in the form given by the pupils is not so unlike the view of Lester and Brazelton: 'We can never measure genotype directly, since our data are anchored in behavior. Behavior (or phenotype) represents the expression of genes manifest in interaction with the environment' (Lester & Brazelton, 1982, p.22).

But the pupils are not aware of the implications of their 'solution'. The original problem of how genetic dispositions relate to the traits of the organism, which came up earlier in their discussion, is still unsettled. In an attempt to summarize their discussion the pupils concluded this about their difficulties:

P1: - - - We're supposed to have learned all that already! But we missed it. I mean ... what we missed, it's ... we've never gone through what's really going on, *from beginning to end*!
- - -
P2: We haven't learned *what it's all about!*
- - -
P3: Yeah, all we've got is some of the *pieces*...
- - - -
P1: We've only learned a lot of *words*.

It would appear that the pupils in both groups had gotten caught up in the problem of physical reductionism without being aware of it. In effect, they do explore the question; the one group by leaving the question altogether - we have only talked about the 'inheritance bit' - and the other group by suggesting a relationship between genotype and phenotype, however in terms of a method to detect the genotype. But since the pupils are unaware that such a problem even exists, they are also unaware that they have arrived at a solution. Consequently, their difficulties remain unresolved and they remain dissatisfied with their own explanations.

7. PUPILS' DIFFICULTIES IN RELATING MICRO TO MACRO

In the instruction the pupils had received, the teacher tried to present a general framework for the studies in genetics. Experiments were made on the breeding of mice of different colours and the pupils had registered the different colours of the offspring. The topic of genetics was introduced by presenting the idea of the evolution of the species and the question of how new species arise. From this general review the teacher went through the different types of cell division and then the DNA molecule was presented. A good deal of time was spent on working with Punnett squares. Then, when the question of mutations came up, the instruction led back to the thesis that an abundance of diversified individuals within a population is one of the central factors in an explanation of the evolution of the species.

Despite this exemplary oscillation between a micro and a macro level, the pupils found the instruction fragmentary. One reason for this is probably that the topic of genetics is a difficult area to grasp and the conceptual system that is presented to the pupils is highly complex (see e.g. Longden, 1982; Stewart, 1982). The context given by the teacher is easily overshadowed by this complexity. When the pupil is trying to understand the construction of the DNA molecule, it is not easy for him to keep in mind the chain of events relating this to the transition of traits. This is a problem of instructional method; but there is also another problem here of more theoretical interest, a problem concerning the relationship between micro and macro levels.

In genetics there is ground for saying that the relationship between the micro and the macro level is itself problematic. Possibly this is a common state in the realm of biology as long as one is studying complex systems occurring in the world around us. In genetics we have the 'behavioural' domain, as Lester and Brazelton (ibid.) expressed it, which coincides in many respects with a common sense domain of concepts and it is this common sense domain, or alternative frame of reference (Driver & Easely ibid.), which determines for what kinds of questions the pupils believe they are to seek the answers.

The pupils define the context for explanation on the basis of their alternative frames of reference. In the case of genetics, it is the transition of traits. When the explanation descends to the level of molecules, the pupils lose the connection with the trait and become confused. They cannot relate their common sense, or macro level of understanding, to the level of molecules, or the micro level. Consequently, the micro level loses its meaning. It becomes merely *'a lot of words'*, as in the excerpt above, and the pupils lose their way in their attempts at explanation, as in the following dialog.

P1: What the hell are we *talking* about?
P2: But you've explained it!
P1: Well ...
P2: But now you have *explained* it!

P1: Ridiculous.
P2: But you can explain *why* it's like that - - - they are bearers of that disposition.
P1: What do you mean? I'm totally lost.

It does not even occur to these pupils that the relationship between the genetic level and the behavioural level can be regarded as a question in its own right, well established in philosophy and the philosophy of science as the problem of *physical reductionism.* If it does not even occur to them that this could be a problem, they cannot deal with it as a problem.

8. DISCUSSION

In summary then, the pupils did not succeed in relating the transition of traits, a problem which could be formulated within their own frame of reference, to the inheritance of dispositions as it is described in the realm of genetics. Actually, this is an unresolved problem, going by the name of physical reductionism (see e.g. Borger & Cioffi, 1970), but since the pupils did not realize this, they tried to solve it and got lost among the byways.

Now, it can be argued that attempts, doomed to failure, to relate a macro level, conceptualized in a common sense frame of reference, to a micro level, presented in an instructional setting, are frequent even in situations where the relation is unproblematic from the scientific point of view. This because: "Whenever the learner encounters a new phenomenon, he must rely on his current concepts to organize his investigation. Without such concepts it is impossible for the learner to ask a question about the phenomenon, to know what would count as an answer to the question, or to distinguish relevant from irrelevant features of the phenomenon" (Posner et al., 1982, pp. 212f).

The success of such an undertaking depends on how the learner's macro level relates to the scientific macro level and it can be argued that these macro levels often differ. The next topic taught to the pupils we studied was the evolution of the species. For the pupils the question of evolution encompasses questions about the driving forces of change, the multiplicity of life forms, nature's apparent functionality and the meaning of it all. These questions lie partly outside of the domain of the Darwinian theory of the survival of the fittest, and they demand answers that are much more far reaching than that theory can provide (cf. Halldén, 1988b).

That different macro levels can account for learners' difficulties in understanding the explanations given in instruction may also account for at least some of the parallells between the history of science and the individual's conceptual development in science. Thompson (1986), for example, when relating the history of the law of inertia, points to the different kinds of questions regarding movement that have been asked. Aristotle's question was *why does the arrow move* when it has left the bow, while Descartes, and then Newton, asked *why does the arrow stop* moving (cf. also Gilbert & Zylbersztajn, 1985). Students asked to identify what forces act upon a hockey puck sliding across the ice often add a force acting in the line of the direction of the puck (Johansson, 1981). Here it is reasonable to assume that the students are answering the Aristotelian question of why the puck is moving at all (cf Halldén, 1988a).

It seems reasonable to claim that the macro level, from the learner's point of view, makes up an alternative frame of reference of its own. Thus we can talk about alternative frames of reference on a *meta level*. This meta level can be defined as the sum total of beliefs determining what kind of questions can be asked in the realm of a specific topic. The meta level requires empirical description in the same way that has been done with regard to beliefs about specific concepts in the 'alternative framework movement' (Gilbert & Watts, 1983). The implications for instruction are to be looked for in the relation between these meta levels and the level of description in the scientific domain. Perhaps we will then find that scientific descriptions and explanations should be regarded more like intellectual puzzles or plays and our aim should not be to alter the pupils' conceptions but to extend the pupils' repertoire of conceptions.

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BIOLOGY EDUCATION AND PARTICULATE THEORY: "TOO MUCH CHEMICALS!"

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1. INTRODUCTION

The title "Too Much Chemicals" was the final summary statement of a small group of 14 year olds writing a report for the rest of their class on an aspect of plant nutrition with one of the teachers engaged on our research project. The work had been concerned with mineral uptake by plants (in terms of the current National Curriculum this is referred to in Attainment target 3-Processes of Life level 7 -know that plants require specific minerals for healthy growth...). They were referring in this instance to fertilisers which they described as chemicals and which were therefore in their view unnatural. The grammar may leave something to be desired but the comment was obviously heartfelt and this together with their previous discussion suggested that the children appeared to be explaining what they perceived to be uniquely biological processes using words like feeding, uptake, over-eating and congestion and either that any chemical explanation was inappropriate or impossible to articulate. They said during interviews that they liked biology and wanted to continue to study it, there were some aspects that they found to be dull but usually it was very interesting and not difficult to understand. However there were some aspects that they found to be very difficult and this was usually, in their view, because these aspects involved chemistry. These pupils were apparently confident and motivated when exploring topics such as predator/prey relationships, ideas of adaptation and survival, growth, life cycles, behaviour, and were able to develop good explanations of quite complex situations. But when faced with chemical aspects of topics such as photosynthesis, digestion and respiration they lost their self confidence to participate in developing explanations of these processes. Other pupils in the same class were on the other hand apparently more confident in handling chemical aspects of biological topics. However these latter pupils appeared to be largely accommodating chemical concepts within their own existing explanations when faced with biological phenomena. One such pupil who could explore the phenomenon of osmosis drawing upon particulate ideas when presented with a laboratory example using visking tubing wrote when discussing the use of fertilisers "..too much fertiliser on plants is bad because it affects the natural growth of the plant, it slows down chemical reactions and the cells of the plant die.", another wrote ".. the necessary plant food, aided by osmosis, is drawn into the plant, inside there is less and it is unable to come out.

With too much fertiliser nothing is able to come out of the roots causing congestion, therefore the plant dies." I seek to explore in this paper aspects of what may lie behind this sort of situation which is not an unusual one in English secondary schools.

Biology is probably best considered as a field of study rather than a single subject. The range and diversity of interest within biology extends from molecular biology, biochemistry and biophysics concerned with the physical basis of life to genetics, evolution, ethology and ecology concerned with the complex relationships of inheritance, behaviour and environment. J.W.S. Pringle (1963) made an important contribution to our thinking about biology when he argued that in essence there are "Two Biologies" with two broad types of concepts: "the one holistic, emphasising function and relationship, seeking an understanding of historical development; the other atomistic, seeking always simpler elements, analysing by controlled experiment". That is there are broadly two ways we go about exploring and describing the living world the first of these he called the biophysical and the second the biosocial. When teaching about biological phenomena at the secondary level we are frequently presenting learners with situations in which we expect them to bring to bear these different styles of thinking and associated conceptual frameworks in interpreting the phenomena in question. This may be confusing for learners, particularly if teachers are unaware of the varying intellectual demands they are making upon their pupils. A study by Millband (1984) of teaching style in relation to different biological concepts showed that teachers in this study did not change their style of teaching in recognition of the nature of the topic.

In handling the biophysical aspects of secondary school science there are explanatory models we need to use that are unique to biology. These are largely structural concepts such as for example, cell, tissue, organ, organism, micro-organism, gene and chromosome derived from direct observation of living things independently of any description of the physical world. However when we seek to describe and explain the processes associated with these structural concepts such as transport of materials into cells, synthesis of new materials, movement etc., we need to draw heavily upon models derived from the physical sciences, especially particulate concepts of matter, but also others such as concepts of work, force and energy. Our "Too Much Chemicals" group of 14 year olds seemed confident in handling structural concepts but their attempts to develop biophysical explanations of these process aspects seems to have been frustrating.

In all cases the living phenomena to which we seek to apply physical science concepts are considerably more complex than the physical phenomena that children will investigate when learning about such concepts. Developing ideas about the nature of matter might involve children experiencing changes of state of matter as a basis for exploring explanatory particulate models. This may then be followed by applying such models to new situations such as melting wax and exploring the compressibility of different materials such as sand, water, and air (Johnston, 1987). The biological phenomena which children traditionally might be expected to apply particulate ideas to are those such as: digestion, osmosis, photosynthesis, transpiration, movement of gases in and out of leaves, movement of materials across membranes, uptake of minerals, respiration, breathing, exchange of gases, ecological adaptations, to mention but a few. Not only are these phenomena inevitably complex, but also when exploring such topics pupils are quite likely to be expected to draw simultaneously upon other conceptual frameworks of the physical sciences.

Arnold and Simpson (1980) in their study of the development of the concept of photosynthesis at the secondary level commented: "No matter how many concrete practical experiences are provided, pupils are still expected to understand that an element carbon (which is solid in pure form) is present in carbon dioxide (which is a colourless gas in air) and that this gas is converted by a pigment (chlorophyll) in a green plant into sugar (a solid - but here invisible in solution) when hydrogen (a gas) from water (a liquid) is added using light energy which is consequently converted to chemical energy". One could add to this that the pupils might also be expected to understand that the carbon dioxide in the air enters the leaves of plants through small pores in the leaf surface, moves through the internal spaces and dissolves into the water on the cell walls and then diffuses into the cells. Here, in the presence of light sugar is synthesised, oxygen is released and diffuses from the cells to the cell surfaces where it comes out of solution, moves through the internal spaces escaping through the pores in the leaves. But, of course, in the absence of light these same leaves will take in oxygen and give out carbon dioxide! Such understanding involves the use of a high level of reasoning.

Biology is still taught largely independently of the other sciences at the secondary level (it may, of course, be just as relevant to say that the other sciences are still largely taught independently of biology!) and in many biology teaching schemes little or no attention has been paid in the past to:

a. identifying within the biological conceptual framework that which may be independent of the need for any physical science concepts;
b. identifying the essential physical concepts implicit in the level of understanding expected;
c. exploring what teaching concerning the physical concepts occurs elsewhere in the pupils science courses, and;
d. devising strategies that would help learners to recognise when such concepts may be appropriately applied to biological phenomena. Small wonder then that studies of children's understanding of biophysical topics such as plant nutrition suggest that many children, even on completion of compulsory secondary education, have a very poor

understanding of these topics (Arnold & Simpson, 1980; Bell, 1985; Bell & Brook, 1894; D.E.S., 1988; Haslam & Treagust, 1987; Marek, 1986; Stavy et al, 1987).

2. OUR EXPERIENCES

In our work in Southampton we are exploring the notions children use to interpret biological phenomena, and have found it helpful to analyse these for teaching purposes, paying attention to the context of learning within a cognitive and personality developmental framework. The personality dimension is of particular importance when considering children's learning at the secondary level, it can significantly affect what motivates individuals and so influence learning (Head, 1980). The seeking for personal meaning is often of great significance in adolescence. (It may be that the "Too much chemicals" group were more concerned with this than were some others). However analysis of children's notions alone will not lead to successful strategies for promoting conceptual change without some analysis of the particular body of knowledge involved which identifies the nature of the change to be promoted.

Concepts that may be relevant to developing an understanding of photosynthesis as a component of plant nutrition at the secondary level are illustrated in figure 1.

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a. Plants are green.
b. Plants grow (these may be more specific i.e. a particular plant -lettuce- is green and grows).
c. Plants do not eat but still grow.
d. Plants grow in soil.
e. Plants need water to grow (plants grow better with fertiliser as well).
f. Plants will not live for long in the dark.
(g. Many animals feed on plants.)
h. Plants do not eat but still grow therefore, they must make their own food.
i. The source of a plant's food must be soil, water, air and light
(j. Animals need food to grow and move. Movement involves energy. Energy comes from food.)
k. Plants do not move but they need energy of light to grow.
l. The food produced in plants is starch.
m. Light, chlorophyll, carbon dioxide and water are needed to produce starch.
n. Oxygen is produced.
o. Carbon dioxide + water + energy + chlorophyll -- gives carbohydrates + oxygen.

Fig.1 A possible development of concepts associated with photosynthesis

We have found such an analysis useful in studying the development of children's notions about plant nutrition up to i, where the concepts can be said to be purely biological involving no theoretical input from the physical sciences. The reasoning is based on direct observation of the phenomena with no need to introduce ideas derived from apparently unrelated phenomena (Pritchard, Buckland & Falconer, 1989). However from j to o concepts derived from interpreting chemical and physical phenomena are required. There is no need here for particulate theory, but when we start to look at the cellular sites of photosynthesis and consider the means by which gases are exchanged with the environment, then a particulate theory needs to be drawn upon. We need for j to o (and for any extension considering the sites of photosynthesis) a more complex analysis than that described above involving a development perspective of the chemical and physical concepts implicit in these ideas. We cannot expect children to apply such concepts to explanations of plant nutrition if they are not using them already. Just as importantly in our experience we must not make the assumption that because children have demonstrated their ability to use concepts in one context that they will do so in all other situations. Others have also reported that when individuals are presented with subject matter that is new to them there may be a "regression effect" (Chiapetta, 1976). This is illustrative of the need to recognise the degree of complexity involved in establishing satisfactory studies of the development of children's ideas of biological phenomena in the biophysical domain. One needs at least, as a component of a research strategy, to make comparisons between those children who have had a coordinated experience of learning science with those who have experienced chemical, physical and biological phenomena quite separately from each other.

There are not "Too much chemicals" in biology teaching, the issue is rather one of coordination of experience and theory making for children so that they may have appropriate opportunities to integrate their developing ideas of the physical world with those they are developing about biological phenomena. What are appropriate opportunities is clearly important to define. They need to be such as to avoid presenting pupils with levels of complexity that they cannot handle. This can lead to the sort of insecurity our "Too much chemicals" 14 year olds seemed to face, a situation they could not handle, which thus led to frustration rather than positive conceptual change. Equally there needs to be frequent opportunities for theory making, and the children's theories need to be valued. There are important implications in this for teachers of the sciences and their training. While physics and chemistry may progress effectively ignoring biological phenomena, when it comes to children learning about the biophysical domain the specialist teachers of chemistry and physics will need to be sensitive to the children's needs when exploring life forms. This is irrespective of whether science is delivered in integrated, coordinated or separate formats-although clearly integrated and coordinated patterns are more likely to provide positive frameworks for teachers to consider the learning needs of their pupils in these respects. Equally there are important implications for developing curriculum materials, we need to see curriculum development more in terms of providing flexible resources that can be adapted to meet changing needs than whole courses that are inflexible.

Teachers working on the Science for Life Project at the University of Southampton have applied some of these ideas to curriculum development and their work in the classroom. They have taken the view that the most effective approach to science teaching is when intellectual scientific problems arise out of prior questions which are both meaningful and important to the learner. Real world themes, such as Pets and People, Marketing Crops, Health and Safety, The Chemist Shop and Managing Resources provide the framework for the teaching. Appendix 1 "How Do Antiperspirants Work" is an example of a piece of practical work, taken from a theme concerned with pharmaceutical products and personal appearance and hygiene (Appendix 2). In this case scientific questions concerning the nature and methods of working of antiperspirants and deodorants arise out of the pupils concern for their personal appearance (adolescents are often very concerned with this, both boys and girls). This provides an opportunity to explore the value of particulate ideas as models for explanations of the phenomena being observed Other extension work allows the pupils, using porous pots and antiperspirants to do quantitative experiments where they relate their particulate ideas to maintaining the body temperature.

When working in this context *all* the children in the class with the "Too much chemicals" group in it were much more confident in handling the scientific ideas presented by the teacher. Those who previously had found the chemistry inaccessible more confidently handled abstract ideas, in this case, particle ideas. Those who had before only successfully applied their scientific explanations to situations they had previously experienced in the laboratory started to apply them with confidence and some accuracy to novel real world situations. All the children seemed to be better motivated and more prepared to apply their minds and energies to the work of the science classroom.

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APPENDIX 1: How Do Antiperspirants Work?

Deodorants do not prevent the release of sweat from the skin whereas antiperspirants do. The following experiments should help you find out why.

TASK
Spray a small amount of the deodorant onto one piece of black paper and a small amount of the antiperspirant onto another. Leave both papers for a few minutes. What difference can you see between the two papers? In your own words try and put forward an idea as to how antiperspirants work using this information.

TASK
An experiment to see if antiperspirant and deodorant alter the rate at which water flows through filter paper.

APPARATUS:

Three pieces of filter paper; Filter funnels; Deodorant and antiperspirant; Measuring cylinder; Stop clocks.

Try and spray equal amounts of deodorant and antiperspirant onto two pieces of filter paper; allow them to dry. Do not spray the third piece of filter paper.

Using the apparatus, design an experiment to see if the rate at which watwer flows through filter paper is altered by antiperspirant and deodorant.

Write a report on your experiment. Mention how you made it a fair test for all three pieces of filter paper and why you used filter paper without antiperspirant or deodorant.

Using your results and information on the structure of the skin, try and put forward, as a conclusion to your report, a scientific reason for how antiperspirants work.

APPENDIX 2: Chemist Shop

TEACHING/LEARNING PROCEDURES

Motivators:	Personal appearance and hygiene. Analysis of data. Vocational.
Type of Activity:	USING SCIENCE (1) Critical analysis of health care product. (2) For personal hygiene and appearance. IMPLICATIONS OF SCIENCE Which health care product to buy. DOING SCIENCE Data analysis; Hypothesis formation; Recording data; Problem solving; Investigations; Presentation of findings.

Learning Pathways

Resources:	Sterile preparation; Safe bacteria/fungi.; Shampoo/-acne creams; Adverts; Information of safe use of micro-organisms.
Safety:	Biological hazard.

THE FUNCTIONS OF ORGANISATIONAL LEVELS IN BIOLOGY FOR DESCRIBING AND PLANNING BIOLOGY EDUCATION

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> .... *That these pores(cells) I say, are yet so exceedingly small that the atoms which Epicurus fancy'd would go to prove too bigg to enter them, much more to constitute a fluid body in them ....*
> (Robert Hooke Micrographia, London 1665)

1. INTRODUCTION

This conference is on: "Relating macroscopic phenomena to microscopic particles: a central problem in secondary science education". The words 'microscopic particles' do not seem to indicate particles that can be seen through a microscope. They refer to models for molecules, atoms, electrons, etc. Or as stated in the quotation mentioned above, to atoms that Epicurus fancied.

In biology microscopical and submicroscopical phenomena and concepts play an important role (Hill, 1986). But the models of the submicroscopical particles are not a part of the teaching of biology. In this paper I will investigate if the macro/micro perspective is a useful tool in research and teaching in biology education .

To analyse this question I have chosen the subject of plant metabolism. I have done this for different reasons.

a. To understand metabolism and its implications in biology, knowledge about macroscopical and microscopical levels is necessary.
a. Plant metabolism is regarded as a difficult subject by teachers and pupils. At the same time it is regarded as an important subject. In order to understand biochemical cycles, energy streams and related ecological, agricultural and environmental problems one has to understand the metabolism in organisms (Johnstone et al, 1980).
b. A lot of international research has been done on learning difficulties and preconceptions related to plant metabolism.
c. At the Department of Biology Education at the Free University research is done on learning difficulties and teaching strategies in plantmetabolism.
d. In the new biology syllabi for senior secondary education in the Netherlands, which will be introduced in a few years' time, understanding the relationships between phenomena and explanations at the different organisational levels will become an explicit target.

I will work out the following paragraphs:

- The development of knowledge about the different organisational levels in biology.
- The visualisation of the content of metabolism in a conceptmap using organisational levels.
- The organisational levels as a descriptive instrument for teaching and learning problems:
  organisational levels and experiences of pupils;
  organisational levels and practical work;
  organisational levels and conceptual difficulties.
- Discussion on the usefulness of the macro/micro perspective for this area of biology teaching.

2. ORGANISATIONAL LEVELS AND THE HISTORY OF BIOLOGY

Hooke was the first to describe cells as the small entities which make up cork. He wanted to find out the cause of the elasticity of cork. To his own surprise he found little pores (which he also called cells). He calculated that there must be 1.200.000.000 of these cells in a cubic inch of cork and he mentioned that the atoms of Epicurus will not be small enough to fit in these cells. In Hooke's time corpuscular theories were well known, due to the work of Gassendi and Descartes. Hooke does not discuss these theories extensively, he just mentions that he cannot imagine particles smaller than the cells he saw (Gabriel & Fogel, 1955; Van Melsen, 1962). The relationships between the macroscopical and microscopical phenomena and the relation between the biological phenomena and chemical and physical explanations, has been the subject of intense debates among scientists from the 17th to the 20th century (Lindeboom, 1971; Fruton, 1972).

Hooke was one of the first who described a microscopical phenomenon (cells) in living organism, in the literary sense, seen through a microscope. It was not until two centuries later that the cell theory was formulated by Schleiden and Schwann. The cell theory was not only a generalised description of a phenomenon that Hooke labelled first. In the nineteenth century something of the explanatory power of the cell concept was known as well. A cell was no longer regarded as a structure that builds an organism like a brick is a part of the house. It was discovered that the cell was the place where a lot of chemical processes were going on. These processes were the explanation of chemical phenomena, taking place in and through living organisms. These chemical phenomena, e.g. fermentation, putrefaction, respiration, had already been observed and used, at the macroscopic level, long before a cellular and chemical explanation was available (Fruton, 1972; Gabriel & Fogel, 1955; De Vries, 1878).

The development of new and better theories went hand in hand with the development of new methods and techniques; e.g., the recognition of microscopical phenomena in all living organisms was influenced by the development and production of better microscopes. It was not until the 19th century the quality and quantity of 17th-century microscopes could be improved. The possibility of measuring the amount of gases provided an opportunity for measuring gaseous exchange in living organisms. Through measurement of gases Lavoisier came to the conclusion that: "In general respiration is nothing but a slow combustion of carbon and hydrogen, which is entirely similar to that which occurs in a lighted lamp or candle, and that, from this point of view, animals that respire are true combustible bodies that burn and consume themselves" (Fruton, 1972).

Before Lavoisier, descriptions of gas exchange could be done and had been done qualitatively only. The concepts used for describing these gases did not have a great explanatory power; they only were sufficient to describe functions in nature. Priestley and Ingenhousz (who laid the basis for the theory about photosynthesis) described the influence of green plants on air as their capability to change 'foul air' (air in which animals died) into 'fine air' (air in which animals could live). So plants had a function in purifying air (Gabriel & Fogel, 1955).

Corpuscular explanations of chemical and physical phenomena were not part of the discussions among biologists after the eighteenth century. Biological scientists only used the concepts and explanations developed by chemical and physical scientists.

Research in the history of biology makes clear that till the 17th century only the macroscopical level of organisms was investigated. Through the development of microscopes the cell was discovered and a lot of different cells and tissues were described. In scientific circles corpuscular theories were well-known. Theories by medical and biological scientists about the role of chemistry in the explanation of phenomena in living organisms were either purely descriptive or speculative till the end of the eighteenth century.

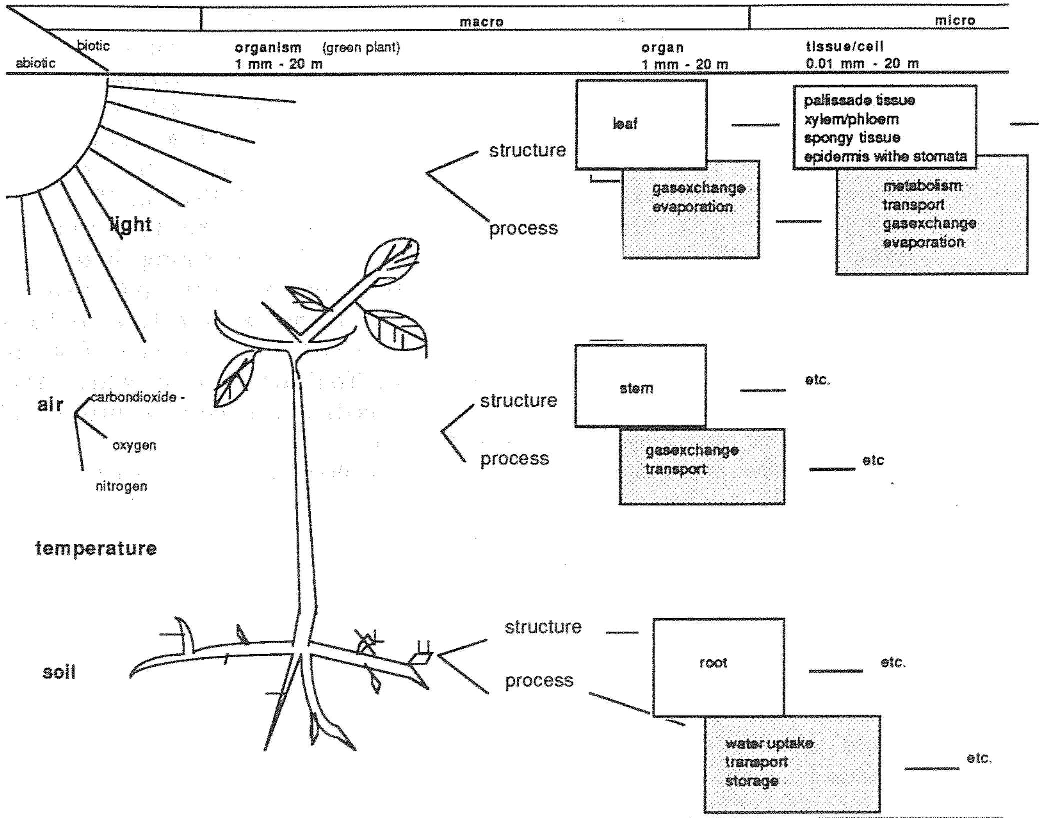
Processes at the subcellular level, which have an explanatory power for macroscopical biological phenomena, could not be fruitfully investigated until basic chemical and physical techniques, concepts and theories had been developed. This happened after the basis for modern chemistry had been laid at the end of the 18th century.

3. THE VISUALISATION OF DIFFERENT ORGANISATIONAL LEVELS IN A CONCEPTMAP

Progress in biological knowledge is largely a matter of developing and refining conceptual frameworks (Mayer, 1982). To get an overview of the conceptual framework of metabolism and the relation with the organisational levels we have made a conceptmap. Boschhuizen developed a method for making hierarchical conceptmaps (Boschhuizen, 1982, 1987).

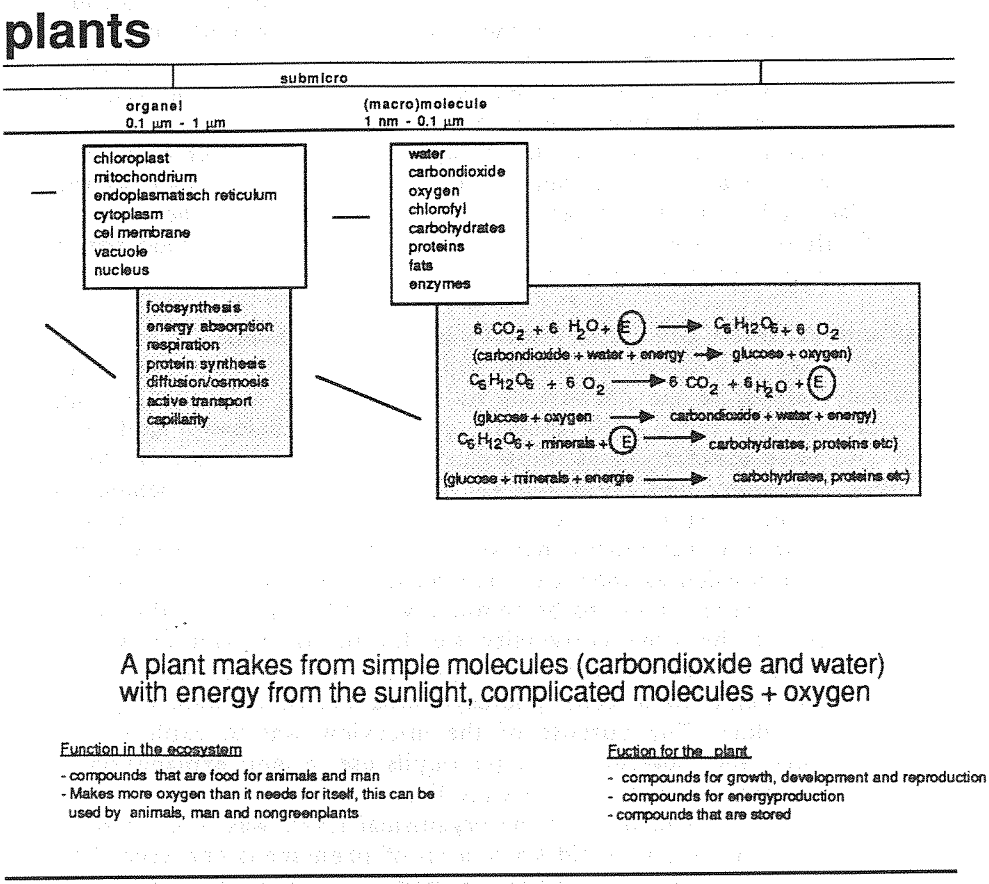
For our purpose we have made a special type of hierarchical conceptmap in the form of a matrix (see figure). All living organisms form

Metabolism of



constitutive hierarchies, being built of organs that are built of cells, the latter being built of molecules. In parts of biology, prominently in physiology and consequently in plant nutrition, cellular and molecular phenomena are used as explanations for phenomena at the organismal level, the so called explanatory reductionism (Mayer, 1982). To understand plant metabolism and its explanations the relationship of the phenomena (structures and processes) at the different organisational levels is important.

In the conceptmap the different organisational levels (macroscopical, microscopical and submicroscopical) are indicated in the horizontal direction. The ecosystem level has been left out for practical reasons. In the vertical direction the organism with its different parts is shown. The map can be made as detailed as necessary, to cover the concepts for a certain level of teaching. E.g. for pre-university training, the submicroscopical level could be specified on the right hand side (showing the different steps in photosynthesis, dissimilation and proteinsynthesis). The concepts



in this map cover the concepts that students have to master in senior secondary education. With the help of this conceptmap, the constitutive hierarchy becomes visible. The concepts in this map have a direct reference to phenomena. Organisms, cells, chemical compounds, water uptake, transport, gas exchange and chemical reactions are phenomena that can be observed and described.

Plant metabolism is an example of a very complex concept that refers to a lot of phenomena and concepts, which can be unravelled as metabolism is in this map.

4. ORGANISATIONAL LEVELS AND LEARNING

The relation between the observation and description of a phenomenon and the formation of concepts is not a direct one. Pupils can observe and describe cells without getting a theoretical concept about cells. A concept only gets explanatory power when it is not described as a phenomenon but when the defining attributes of the concept are recognised, and when it can be related to other concepts. Cells can only be used as explanations if some of the structure of the cell and processes taking place in the cell can be related to phenomena on a higher level.

It is important to know at what level pupils have experiences with phenomena and at what level we can provide experiences in school. In the second place it is important to explore the question whether the conceptual difficulties that are described in literature, can be understood better when the focus is on the organisational levels.

Organisational levels and out of school experiences of pupils

It is clear that experiences of pupils and most people in everyday life, are mainly related to the phenomena on the left hand side of the map; the organism and the abiotic factors, sun, air, temperature and soil. Pupils also have experiences at the organ level, different types of flowers, trees, vegetables and fruits but few at the cellular and biochemical level. They know fruits can be sweet and they probably know wood, flower and starch as substances that are made by plants. These phenomena are seldom labelled as chemical phenomena. When pupils enter secondary school, we expect them to be familiar with phenomena at the organismal level. At the Free University we did research together with a group of teachers. Teachers interviewed pupils in senior secondary school who had been taught about cells, photosynthesis and combustion in plants in junior secondary. The purpose of the interview was to explore how much of cellular and molecular concepts pupils use in their explanation of situations, concerning plants, in everyday life.

Experience, with phenomena at the organismal level, was discovered to be very variable. Some pupils did know a lot of phenomena and used their experience in their reasoning, others seemed to have never consciously looked at any plant. The way they talked about the relation between phenomena at the organismal level and the cellular and biochemical levels was very confused; this was also the case with pupils who knew a lot about plants from their own experience.

Practical work and the possiblities to get experience at the different organisational levels

In practical work we do not study concepts, we study phenomena. By studying phenomena pupils should be helped to recognize the phenomena and to develop concepts. This means that they should learn to observe the defining attributes of concepts.

How easy is it to get experiences with phenomena at different organisational levels in biology? It is easy at the organismal level. At this level pupils can get a lot of experience with macroscopic phenomena. By manipulating a plant or an animal or their parts like roots, stems etc. All senses can be used in observation. A generalised picture of what a (part of a) plant or (part of an) animal is, can be supported by this experience of looking (proportions, color and form), feeling (dimensions, temperature, softness, firmness, humidity) smelling etc. Although manipulating plants is easy, this doesn't mean that it is self-evident that concepts are formed when this takes place. The tasks pupils get in practical work will strongly influence the quality of concept formation.

Experience at the cellular level is very different. The microscope is between the object and the observer and makes observation considerably restricted. No direct experience is possible through touching. The muscles together with the eye are not able to decide about the proportions of a three-dimensional form. The microscope magnifies, proportions are not what they seem to be. Colours are different with light that falls through the object; red blood cells and chromoplasts in tomato cells look greenish in stead of red. You never see one cell but always a tissue. Only intellectual reasoning about the relationship between the manipulation of the microscope and what one sees with different manipulations gives a possiblity for interpretation. In fact most pupils need to have some concept of what a cell is otherwise they will never discover them under a microscope. They also need time and directed tasks to relate the phenomena they see under the microscope to what they know at the macroscopical level and what they know about the cell concept.

Biochemical structures are not visible in living organisms. They are part of the macroscopical and microscopical phenomena but they are hidden in them, never pure, always in a complex relation to each other. This is very different from the macroscopical phenomena in chemistry. In biology pupils get a glimpse of organic molecules by using indicators. If a substance is present it will show itself through a colour, nothing more. Indicators don't give any information about stucture, proportions, rigidity of molecules. The practicals that can shed more light on these phenomena are mostly hypothetical and deductive. Careful reasoning is important in these practicals. What a molecule looks like, how much there are in one cell, how they move around the different organelles, will not be shown in these practicals (Alderwegen, et al, 1988).

Chemical and physical phenomena which are important in biology, besides the biochemical, are the abiotic factors in the surroundings of organisms. They are not as hidden as the biochemical phenomena. The warmth and the light of the sun can be experienced by everybody, the air flows around everybody and we all stand with our feet on the soil from time to time. In biology teaching, in general no practicals are done to help children to develop concepts about these phenomena. That is part of the chemistry and physics lessons. But not all the pupils choosing biology in senior secondary also follow lessons in chemistry and/or physics (Alderwegen, et al., 1988).

In practicals techniques have to be used that make observation and interpretation of phenomena possible. However, learning the necessary technical skills interferes with concept learning. The more attention has to be given to planning experiments and using techniques, the less time and place there is for reasoning and concept formation (Johnstone, et al., 1982; Kapteijn, 1988).

Up till now there are hardly any Dutch biology textbooks available that show an insight into how to organise practical work in relation to concept development at different organisational levels.

Conceptual difficulties on the different organisational levels

What are the learning difficulties described in literature about plant metabolism up till now?

One group of learning difficulties can be described as the formation of concepts at the different organisational levels. A second group of difficulties has to do with relations between the different concepts.

Formation of concepts at different levels

Organism.

Pupils can use the word plant correctly in conversation, they know examples and can differentiate in concrete situations between examples and non examples. It is often assumed in classrooms that pupils have a stable concept of what a plant is. From research at the University of Waikatoo we know that a lot of pupils don't know the defining attributes of the concept plant (Stead, 1980).

The same holds for the concepts animal (Bell, 1981; Tamir et al., 1981) and living things (Tamir, 1981; Brumby, 1982; Stead, 1980).

Cells

The work of Dreyfuss and Jungwirth (1989) and the work of Schermer (1988) reveals that pupils in junior secondary, who have been taught about cells and have seen cells through a microscope, do not have a concept of cell that has the necessary defining attributes. The concept even has attributes it should not have.

Biochemical factors

Energy conversion from light to a chemical compound is magic as long as concepts from physics and chemistry are not available. And even if they have learned about chemical compounds and energy, transfer to biology will not automatically take place (Stavey et al., 1987; Vlijtig Liesje, 1989). In general pupils have no idea about dimensions of molecules in relation to cells (Van Dijk, et al., 1989).

Abiotic factors

As long they are not taught any physics pupils don't have a stable concept of light that is related to energy. They think that light could be matter as well (Stavey, et al., 1987), contains vitamins and makes plants healthy (Vlijtig Liesje, 1989). They don't realize that (both) light and warmth are aspects of the same phenomenon, and that they have different functions in plants (Van Dijk et al., 1989). They have difficulties perceiving gas as a substance which has weight and dimensions.(Stavey et al., 1987; Wandersee, 1985; Simpson et al., 1982).

Relationships between concepts at different levels
Pupils don't think about their own body, and they probably don't think about plants as chemical systems either (Stavey et al., 1987). Comprehending the relationship between food, photosynthesis and respiration is very difficult (Simpson et al., 1982b; Haslam et al., 1987; Stavey et al., 1987).

The organism everybody has most experience with, is her or his own body. It is to be expected that real preconceptions (deeply rooted) about life and living processes have their origin in the life long experiences that pupils have with their own body.

Pupils do not distinguish concepts at the organismal level from related but different concepts at the biochemical level. It is rather difficult to relate breathing (gas exchange) to and distinguish it from respiration (biochemical energy conversion). Food is also a difficult concept. It is used in everyday life and by biologists for a phenomenon at the organismal level, the intake of nutrients. But it is also used for a compound, rich in energy, that is formed in photosynthesis and used for respiration and making other organic molecules. All pupils know that green plants produce oxygen and they themselves use oxygen. So they regard photosynthesis as an upside down type of respiration. They don't realize that photosynthesis and respiration do both take place in plants during daytime, at the same moment and that oxygen production is the net result from produced and used oxygen.

Comprehension of the significance and the function of metabolism of plants for the plant itself and for the ecosystem is also very difficult to achieve (Stavey et al., 1987; Bell, 1985; Bell et al., 1984; Barker et al., 1989, Wandersee, 1985, Vlijtig Liesje, 1989). Which is not difficult to imagine after all the problems mentioned already.

5. DISCUSSION

We now come back to the question in the introduction. Is a macro/micro perspective useful in biology? For me the answer is yes. Concept-formation at the cellular and biochemical level is important if we want pupils to learn explanations of macroscopical phenomena. Concept-formation at the cellular and biochemical level does not take place easy. Although teachers can give concrete experiences at those levels, pupils cannot form concepts from these experiences only. They need models to get a picture of what is happening, especially at the biochemical level.

These models are taught in Dutch education in chemistry and physics lessons. The order in the curricula doesn't guarantee that this happens at a moment when it is needed for understanding biology. In senior secondary there are pupils who have to make do with what they have learned about chemistry and physics in junior secondary. Two questions need to be answered before we can start planning more orderly.

- What are the possibilities of 12-15 year old pupils to learn something at all about chemical and physical concepts?
- To what extent do pupils need to understand physical and chemical concepts in order to comprehend the metabolism of plants, the function of metabolism for the plant and the function of plants in the eco-system?

Besides the difficulties at the cellular and biochemical level there is other matter that needs more attention.

Research has made clear that concept-formation at the organismal level is lacking. Little attention is paid to this in senior secondary textbooks. Barker (1989) proposes that teachers should not try to reach comprehension of metabolism by introducing concepts at the cellular and molecular level right from the beginning. He first wants to create coherence in the experiences and concepts that pupils already have. The relationship between the intake of water, gaseous exchange and production of wood can be taught without reference to cellular and biochemical concepts. He suggests teachers should proceed to the cellular and biochemical explanations only after this coherent picture has been achieved.

The relationship between the different levels is a problem too. In books concepts from different levels are dealt with in different chapters. In textbooks there is never a place for integration. In teaching materials more attention should be paid to learning activities aiming at integration.

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WHY DO SOME MOLECULES REACT, WHILE OTHERS DON'T?

On the use of corpuscular concepts in teaching and learning a dynamic equilibrium model in chemistry

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1. INTRODUCTION

In chemistry education chemical reactions are usually introduced as processes involving the conversion of substances into other substances. These conversions are initially always being presented as proceeding to completion and as taking place in one direction only. When the concept of 'chemical equilibrium' is introduced at a later stage, the possibilities of chemical reactions *not* proceeding to completion and being reversible have to be taken into account. This requires a revision of the chemical reaction concept.

When introducing the chemical equilibrium concept, most schoolbooks (both Dutch and foreign) emphasize the so-called 'dynamic' nature of such an equilibrium. This means that in a state of equilibrium two opposite reactions are supposed to take place at equal rates. This idea is usually described in corpuscular terms.

In this paper we will report some results of an empirical study concerning the introduction of a qualitative chemical equilibrium concept. In this introduction emphasis is placed upon the 'incompleteness' of a chemical reaction. A dynamic equilibrium model is offered as a possible explanation for this experimental fact. Special attention in this paper will be paid to the relation of the dynamic nature of chemical equilibrium with corpuscular notions. First however, we will make some remarks about the scope of our research and our research method.

2. SCOPE AND METHOD OF OUR RESEARCH

Learning is, in our view, a process of constructing and revising concepts. It can therefore be seen as 'conceptual development'. Learning can take place when learners observe and discuss 'phenomena'. Teaching should be aimed at promoting conceptual development. It involves the organization of situations in which learners (i.e. students) are encouraged to discuss their concepts. We think this can be most efficiently achieved if students work in small groups (of three or four). In this view a teacher should select appropriate 'phenomena' and lead a discussion of students, rather then telling students 'the scientific knowledge' straightaway. Apart from asking them questions, a teacher should encourage students to ask questions themselves. Broadly speaking we adopt a constructivist view of learning (a more detailed description of this view is, amongst others, given by Driver, 1988). For the purpose of this paper, we want to stress the following features.

We distinguish between two types of learning: one of these can occur when students are confronted with new situations, which are in accordance with their existing concepts. This process can be characterised as "learning more about the same". The other process may take place when students are confronted with a situation in which they cannot adequately use their present concepts. In such a 'conflict situation', a student may revise his or her concepts quite *radically*. If this happens (which will depend on the situation), we speak of "learning something new". In order to facilitate this type of learning, teaching should focus on the organization of 'conflict situations', in such a way that a radical concept-revision process is being promoted.

In our work, this latter type of learning is crucial. A succesful teaching attempt is described by two of us. (It concerns an introduction of the concept of 'chemical reaction'; De Vos & Verdonk, 1985).

From this approach to teaching we derive implications for research. A general teaching strategy that can be succesfully applied to "learning something new" is, in our view, not available. If we want to teach a subject, e.g. 'chemical equilibrium', we must:

- describe students' exisiting concepts and what revisions or developments seem necessary;
- organize classroom situations, in which the desired concept revision processes can take place. This involves selecting (chemical) experiments and formulating questions and texts for students, and also instructions for teachers.

These activities are strongly connected with the content of the subject. But neither of them can be performed succesfully on the basis of an analysis of scientific concepts only. In our view, it is necessary to combine such an analysis with a study of the way students and teachers observe the phenomena and handle the concepts in their classroom. Therefore the study of group discussions is essential in our work.

The work we report on in this paper is organized as follows: it started with an analysis in chemical terms of concepts related to chemical equilibrium. Schoolbooks dealing with this matter were also studied. On the basis of this analysis a first version of an experimental course on the subject 'chemical equilibrium' was designed. This was used in several Dutch schools. One of us visited some of these schools in order to observe teachers and students, the latter working in small groups with the course. Audio-tape recordings of discussions were made and written out afterwards. The transcripts obtained constitute the main body of research material. Written reports of groups of students were collected as additional material.

Analysing this material stimulated our interest in the historical development of the equilibrium concept. The combination of a historical study and the analysis of students' discussions led to a better understanding of the concept revisions needed, and of learning and teaching problems connected with these. On the basis of this understanding, we worked out a second version of the experimental course and repeated the process of observing students and teachers, analysing their discussions, etc.

The final goal of this research is to describe a so-called 'educational structure'[1] of the concept of chemical equilibrium. This should consist of a detailed description of the most relevant chemical concepts (contents, relations between them) and of the concept revisions needed; of learning and teaching problems involved, and of suggestions for teaching aimed at overcoming these problems.

3. THE INTRODUCTION OF A QUALITATIVE DYNAMIC EQUILIBRIUM CONCEPT

An introduction of 'chemical reaction'

In the Netherlands, education in chemistry starts in the third year of secondary education (in certain types of school only)[2]. The average age of students is then 14. In this first year the curriculum consists of ca. 60 hours, the crucial topics being the concepts of 'substance', 'reaction' and 'element'. These concepts are usually introduced and developed on two levels: both a macroscopic level (at which experiments may play an important role) and a corpuscular level are prescribed by our national curriculum (in Dutch: "leerplan") for all three concepts mentioned.

For the purpose of this paper it is important to note that the chemical reaction concept is being dealt with in most schoolbooks as follows.

- On a macroscopic level chemical reactions are introduced as events in which the original substances disappear while other, new, substances are being formed. These conversions are accompanied by observable effects, such as color changes, evolution of gases, energy effects, etc. The possibility of a reversion of these conversions is not yet taken into account. In other words: at this stage chemical reactions are implicitly supposed to take place in one direction only.

  One aspect of chemical reactions emphasized during this stage of chemistry education is the constant mass ratio according to which substances react. The usual interpretation of this principle is, that if reactants are mixed in the 'required' mass ratio, no excess quantities will

1. In Dutch 'didactische structuur' (German: 'didaktische Struktur'). Further information on this expression is provided (in Dutch) by Van Driel et al. (1988).
2. For more information see Ministry of Education and Science (1988).

be left over after the reaction. In other words chemical reactions are initially being regarded as proceeding to completion.

- A substance corresponds with a molecular species at the corpuscular level. Molecules of the same species are regarded as identical, that is: they do not differ from each other in any way except position and motion[3].

As a consequence, a chemical reaction at the corpuscular level is considered to be a conversion of molecules of the original species into molecules of one or more new species.

At this level, excess quantities mean that some molecules remain unchanged, because of the absence of reaction partners.

In a typical example two hydrogen molecules will react with one oxygen molecule to form two water molecules, according to the reaction equation $2H_2+O_2 \longrightarrow 2H_2O$. In this case the corresponding mass ratio is 1 g of hydrogen : 8 g of oxygen (yielding 9 g of water).

Implications for teaching 'chemical equilibrium'

The concept of chemical equilibrium is usually introduced during the second year of chemistry education. Some of the notions described above need to be revised when this concept is introduced, because in the case of a chemical equilibrium the reaction under consideration does *not* proceed to completion, and appears to be *reversible* as well.

Moreover, chemists suppose that in a state of equilibrium two opposite reactions take place at the same rate, although this cannot be deduced from direct observations. Because of this assumption, a chemical equilibrium is said to be 'dynamic'. It is important to notice that the idea of 'two opposite reactions taking place' is purely hypothetical. These reactions are being assigned to an equilibrium state on the basis of theoretical arguments; from an observer's point of view 'nothing happens' in a state of equilibrium. Therefore, we prefer to speak of a 'dynamic equilibrium *model*'. As stated above, every chemical reaction students had met with so far was accompanied by observable effects. Thus the idea of hypothetical, 'unobservable' chemical reactions is new to them.

To illustrate the equilibrium concept we turn again to the reaction of hydrogen and oxygen. Under certain circumstances (temperatures above 1700 K), this reaction does not proceed to completion and also appears to be reversible. Under these circumstances the reaction equation is usually written as $2H_2+O_2 \rightleftharpoons 2H_2O$. In any state of equilibrium all substances concerned (hydrogen, oxygen and water vapour) are present in constant quantities. In such a state it is not possible, however, to calculate these quantities in the way mentioned above: 1 g of hydrogen and 8 g of

3. In earlier work, two of us have paid attention to the development of this aspect of corpuscular notions in the first year of chemistry education. See for example De Vos (1985) or De Vos and Verdonk (1987).

oxygen will not yield 9 g of water, but less. At the same time, amounts of both hydrogen and oxygen will be left over.

Teaching the concept of a (dynamic) chemical equilibrium thus requires one to aim at revisions in some of the concepts taught up till then. Two of these revisions arise from the changes to 'two directions' and to 'not proceeding to completion'. In this paper however, we will focus on revisions that are connected with the introduction of the dynamic nature of a chemical equilibrium, especially in connection with the development of corpuscular notions. In this context the following questions are relevant:

1. Is it, from a *chemical* point of view, *necessary* to connect the introduction of this dynamic equilibrium model to corpuscular concepts?
2. Is it, from an *educational* point of view, *advisable* to connect the introduction of this model to a further development of students' corpuscular notions?

In order to answer these questions, we will report some results of our empirical research. As we stated above, we designed an experimental course on 'chemical equilibrium' within the framework of our research. In the first version of this course the introduction of the concept of chemical equilibrium can be described as follows.

- First students performed an experiment in which a test tube containing a homogenous solution was repeatedly heated and cooled in the temperature range 20°C to 85°C. At low temperatures the color of this solution is pink, whereas at high temperatures it is deep blue. At intermediate temperatures a range of purple colors is visible[4].
- Next students thermostated this solution at ca. 55°C. The course continued with a series of questions concerning this particular state. These questions served to make it acceptable for the students that (1) the reaction under consideration was reversible; (2) this reaction did not proceed to completion at 55°C and (3) it is reasonable to assume that at 55°C both the forward and the reverse reaction take place at the same rate. The expression 'chemical equilibrium' was introduced in the course only after this series of questions. It is important to state that this version of the course did not contain any references to corpuscular notions!

Some typical examples of group discussions

We now present a few transcripts of (parts of) discussions that we have recorded in groups of students working with this version of the course.

The first transcript was recorded while a group was heating a solution

4. This solution was made by solving 1 g of cobalt(II) chloride hexahydrate ($CoCl_2.6H_2O$) in 25 ml of 2-propanol and (after the solid had disappeared completely) adding a few ml of distilled water, so that the color of the solution at room temperature had just changed from blue to pink. A description of the system in chemical terms is given by Spears Jr. & Spears (1984).

to 55°C (after having performed the 'heating-and-cooling-experiments' first). They were asked to describe their obervations:

Transcript 1[5]:

1	john	it's getting a bit purple
2	ann	it only goes very slowly
3	john	no, it's not going slower, it only goes to a certain point
4	ann	yes, that's what I think as well
5	lisa	yes, to the point of fifty-five degrees
6	mike	no, not according to me. If you keep the tube at fiftyfive, the reaction goes slower, but at a certain moment it will be completely blue again
7	john	no, I don't think so
8	ann	no
9	mike	for why will some molecules of the same substance be converted and others not? That doesn't make sense! They're all the same substance, so they all have the same properties. So they will all be converted. It only will go slower
10	lisa	hm yes, that makes sense
11	john	makes sense indeed

The group in this transcript deals with the problem of whether the reaction will proceed to completion or not. In 3, John states that the reaction will be incomplete. This is a hypothesis, for it cannot be concluded from the observations whether the color is 'absolutely constant' or 'changing very slowly'. Although John does not give an argumentation for his hypothesis, Ann and Lisa seem to agree with him. Mike obviously doesn't. In 6 he states clearly that according to his view, the reaction will finally proceed to completion. In 9 he supports his view with a corpuscular argument. Lisa and John fail to argue against Mike. The discussion ends after 11. As we stated, the experiment does not offer direct proof for either one of the two views.

We consider Mike's argument to be very important. He uses the concept described above, that molecules of one species are identical. According to this concept, which has been taught previously, any reaction *should* proceed to completion. In other words: this concept blocks the acceptance of the idea that chemical reactions can be incomplete. Teaching the incompleteness of a reaction at the corpuscular level, thus requires a revision of this corpuscular concept. Although we initially chose not to

5. Utterances are being numbered in chronological order; names are fictitious, although male names refer to boys and female names to girls.

connect the incompleteness with corpuscular notions, this transcript shows that students may make this connection themselves.

The course continued with a series of questions. No further information on 'the situation at 55°C' was provided. Via one of the questions, the dynamic equilibrium model was put foward:

"Do you think that one of the two, or that both reactions, actually take place if the temperature remains at 55°C?"

The second transcript concerns the same group, discussing this question.

Transcript 2:

1	mike	it could well be that reactions are taking place
2	lisa	yes, it can go back and forth, can't it?
3	mike	yes, it can go back and forth
4	john	oh yes, in one part of the substance it gets a bit warmer, for example at the surface there'll be more...
5	lisa	well, if that happens at the same time, then no colour change
6	john	or for example at the outer sides, they are somewhat warmer, while the inner sides are somewhat colder
7	lisa	but if they only happen at the same moment, every time, then there will be no color change
8	john	but suppose that it really remains at fifty-five degrees, just absolutely constant everywhere, then there will be no reaction anywhere

In 2 and 5, Lisa suggests the possibility of two reactions taking place at the same time. On the other hand, John's reaction concept is connected to macroscopic phenomena. According to his concept, a reaction can only occur if local (minor) temperature differences exist. This concept is in accordance with the reaction concept taught so far, but for the dynamic equilibrium model to become acceptable it is necessary to reason in terms of 'unobservable reactions'. None of the students in this transcript gives an argument in these terms. Therefore the road to the dynamic equilibrium model is blocked.

In another group the same question gives rise to the following discussion:

Transcript 3:

1	rik	yes, both, they both take place at the same time
2	pete	both at the same time? That's not possible. How is that possible at the same time?

3	rik	these reactions always take place together and if temperature changes, one goes faster than the other
4	pete	at the same time? For example, first the pink substance turns into blue, and then, uh, after that, this substance suddenly feels like, uh, getting normal again?
5	rik	you shouldn't picture a substance as one thing, but as billions of particles and some of these particles unite, and some particles split up again

Rik does not seem to have any doubts about the possibility of two reactions taking place at the same time. At first he does not express a solid basis for his opinion, but Pete forces him to do so. In 4, Pete formulates a rather naive reaction and substance concept. Rik 'corrects' this view in 5 by formulating a corpuscular concept. In this concept the reversibility of the chemical reaction under consideration is taken into account (via the use of the word "unite" in combination with "split up"), so that in his view 'particles' of the same species can undergo different transformations "at the same time". His corpuscular concept therefore may include statistical notions. As a result the dynamic equilibrium model becomes accessible.

Finally we present a transcript of a discussion that took place in yet another group, working with a later version of our course. In this version the same question as above was raised, but the experiment preceding it differed from the one described above. In this version the color change from blue to pink was achieved by adding water to a blue solution, while the reverse color change resulted from adding a solution containing chloride to the pink solution. These color changes were then described in terms of reaction schemes (blue substance + water → pink substance + chloride and vice versa). The question under consideration is put forward after students (guided by a series of questions) have come to the conclusion that in a purple solution all four substances concerned are present in constant concentrations. Although this version of the course contains references to corpuscular notions at some places, the question is formulated in non-corpuscular terms: "Do you think that these reactions actually will take place?"

The discussion proceeds as follows:

Transcript 4:

1	dave	no, because the concentrations don't change
2	bob	but if they happen just as fast in one direction as in the other...
3	dave	yes, then it remains the same

4	bob	I don't see a reason why these reactions should not take place
5	paul	because in that case you would see that
6	bob	well look, if the blue substance and water turn into the pink substance and chloride, but in the meantime the pink substance plus ...
7	paul	no, another, somewhere on the other side of the tube
8	bob	... the pink substance and chloride turn into the blue substance and water, so eventually it looks as if nothing changes, while in fact it is busy reacting
9	JvD[6]	but isn't it much easier to say that nothing happens, that nothing reacts?
10	bob	no, but these substances react if you put them together...
11	paul	so why should they...
12	bob	why shouldn't they react if they are already mixed together?
13	JvD	yes
14	paul	I think that makes sense ... I wouldn't have thought of it myself.

In this transcript Bob's arguments especially attract our attention. He is using a model which we can describe as follows: if substances react under particular conditions, then they must always do this if these conditions are fulfilled, even though changes may not be observable. In the case of the reaction under consideration, the 'conditions' mainly consist of the presence of the reacting substances and the possibility of 'contact' of one with the other ("mixed together" in 12). Bob can explain the absence of observable changes by assuming that two opposite reactions take place at the same rate (see 2), therefore cancelling each others effects (see 8). In this way Bob formulates a dynamic equilibrium model, without having to mention corpuscular notions.

Some relevant aspects of the history of 'chemical equilibrium'

As we stated above, the study of classroom discussions like the ones cited above stimulated our interest in the historical development of the chemical equilibrium concept. In particular we wanted to know on what ideas the dynamic equilibrium assumption was orginally based. In this paragraph we will summarize briefly the scientific genesis of this concept[7].

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6. Jan van Driel being present during this discussion in his role as researcher.
7. For further reading on this topic we recommend articles by Lund (1968), Snelders (1977) and Laidler (1985).

In an article published halfway the last century A.W. Williamson writes about the "dynamics of chemistry". His starting-point was the assumption that in a pure substance atoms are being permanently exchanged between the different molecules in a substance. In order to explain why some reactions do not proceed to completion, he assumed that the formation of products continues in those cases, but that the conversion of products to the original reactants also takes place, the absolute numbers of atoms being exchanged per unit of time in both processes being equal. In this respect, Williamson pointed at the experimental fact that such reactions are reversible (Williamson, 1851-54).

A few years later Rudolf Clausius published a molecular-kinetic theory of evaporation, the basis of this being the idea that individual molecules of the same type can have different velocities at the same temperature. In his view, the phenomenon of evaporation of a liquid can lead to a state of equilibrium, in which on the average as many molecules pass into the vapour phase as into the liquid phase. A state of equilibrium therefore is, according to his view, not a state of rest (Clausius, 1857).

In the same period, it became known that within a certain temperature range, some gaseous compounds are only partially dissociated (e.g. ammonium chloride to NH_3 and HCl). The first scientist who gave a correct explanation of this phenomenon, was the Austrian physicist Leopold Pfaundler. In an article published in 1867 he elaborates the ideas of Clausius. First he puts forward two possible explanations for the partial dissociation: *either* all molecules have undergone the same change (the cohesion has become more loose and the distance between the atoms has increased) to reach a state which is between the completely bound and the completely dissociated state; *or* a fraction of all the molecules is completely dissociated, while the rest are completely bound.

Pfaundler rejected the first explanation because it didn't account for certain experimental facts (E.g. Von Pebal had shown that both NH_3 and HCl were present in the ammonium chloride vapour). But he also made objections against the second explanation, because he noticed a conflict with the idea that molecules of the same species should be identical: from this point of view one cannot explain why some molecules break up, while others remain unchanged. Nevertheless he accepted this explanation by adopting Clausius' idea that not all molecules are in the same state of motion, so that, at constant temperature and pressure, at any moment some molecules can decompose while new ones are formed by collisions. In a state of equilibrium the number of molecules decomposing within a certain period of time must equal the number of molecules being formed. (Pfaundler, 1867).

From this short review, we may conclude that

- the dynamic model of a chemical equilibrium was included from the very beginning of the genesis of the equilibrium concept;
- this dynamic model was based on a molecular-kinetic theory. Essential in this theory is the idea of different states of motion for individual molecules of the same species. For the dynamic model to become accep-

table, the corpuscular concept had to be extended with statistical notions.

Conclusions

In this final paragraph we will try to relate our findings in the historical field with our empirical results. We are intrigued by the near resemblance of Pfaundlers arguments to the statements of Mike (in transcript 1, 9) and Rik (transcript 3, 5). Both Mike and Pfaundler have raised a question concerning the possibility of identical molecules undergoing different changes. Pfaundler could solve this problem by including statistical notions in his corpuscular concept. His solution resembles Rik's argument. Statistical notions were absent however in Mike's arguments. Therefore he failed to accept the incompleteness of a chemical reaction.

Thus we suggest that for this incompleteness to become acceptable for students, they should extend their corpuscular concepts with statistical notions. If this happens, the dynamic equilibrium model may become attractive for them, as it can offer a simple explanation for a chemical conversion being incomplete.

We do not want to suggest however that the historical development of the equilibrium concept should serve as a guideline for teaching. We can illustrate this by returning to transcript 4. In this transcript, Bob gives an argument which leads to a dynamic equilibrium model although he does not refer to corpuscular notions. Essential in this is the idea that a reaction will occur if all (macroscopic) conditions are fulfilled. We suggest that this argument offers an alternative road to a dynamic equilibrium model, which may also be attractive for students in order to explain the incompleteness of a chemical reaction.

Returning to the questions we raised in section 3.2, we come to the following conclusions:

1. A dynamic equilibrium model is not necessarily corpuscular by nature. Although the historical origins of this model are connected with a molecular-kinetic theory, one can give an alternative formulation in non-corpuscular terms. An example is shown by Bob's argument.
2. We have no definite opinion about the question of whether to teach the dynamic model from an explicit corpuscular point of view or not. This we may illustrate by returning to transcript 2. Here the dynamic model is not acceptable, since a chemical reaction is related to macroscopic phenomena (especially by John), i.e. temperature differences. We feel that both corpuscular and non-corpuscular forms of argumentation could have helped the students of this group to accept this model eventually. One reason we might favour a 'historical', corpuscular approach towards the dynamic equilibrium model, is that it offers an opportunity for a development of the corpuscular concepts of students. From a corpuscular point of view, the dynamic model requires the inclusion of statistical notions. These notions are usually lacking in the concepts of students up till this stage of education. We suggest that students may find it easier to approach them if the incom-

pleteness of a chemical reaction (following as a conclusion from experiments) is connected with the question in the title of this paper.

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SEVEN THOUGHTS ON TEACHING MOLECULES

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1. INTRODUCTION

Several aspects of teaching molecules and atoms at secondary school level were discussed at the Woudschoten seminar. Some reflections on formal and informal discussions in which the author of this paper participated are reported here. The topics raised in each paragraph are mutually linked in many ways; nevertheless they are presented in seven more or less separate paragraphs in order to make reading (and writing) easier.

The following paragraph considers modern evidence for the existence of atoms and molecules and the educational implications it may have. The third paragraph looks at a possible philosophical and educational justification for assuming the existence of atoms and molecules in order to explain chemical change. In §4 children's ideas on particles are related to a medieval theory which attributed all substance properties to the so-called 'minima naturalia', thereby offering an alternative to Democritos. A series of statements by a student aged 15 who claims dissolved sugar to be a solid is analyzed in §5. The sixth paragraph takes a closer look at the criteria for attributing macroscopic properties to atoms and molecules in science education. In §7 an attempt to develop the substance concept simultaneously on the macro and on the micro level is described. It argues that 'molecular species' rather than 'molecule' is the corpuscular concept corresponding to the substance concept on the macro level. The final paragraph takes the view that learning models as if they were facts does not help children to understand science; education in science should make the child experience the tentative and provisional nature of a model, not only in the intellectual but also in the emotional sense.

2. LOOKING AT MOLECULES

In a well-known textbook on physical chemistry (Atkins, 1986) the first chapter begins as follows: "We know that atoms and molecules exist because we can see them, figures 0.1 and 0.2." The first of these two figures shows a more or less symmetrical pattern of black dots of different sizes, the larger ones being surrounded by a number of concentric circles. It is an image of the tip of a platinum needle, obtained by field-ionization spectroscopy. The second picture, obtained by X-ray diffraction, shows contours of constant electron density in a molecule of anthracene. The pictures suggest that beyond the limits of what the naked eye can see we have not only magnifying glasses and microscopes but also more sophisticated and powerful devices that allow us to look deep into the world of small things. It seems that looking at a molecule does not fundamentally differ from looking at a chair or at the moon.

Do such pictures really prove the existence of atoms and molecules, as Atkins claims? I suppose they do, but only for those who understand the experimental technique that was applied in each case. Interpreting the pictures as convincing evidence for the existence of atoms and molecules requires a long and difficult learning process. The ability to 'see' atoms and molecules in these pictures is not the start but a result of this learning process. "We" in the sentence quoted from Atkins are physical scientists and advanced students of physical science, not lower secondary school pupils. Besides: most scientists were convinced of the reality of atoms and molecules already long before these pictures became available. In fact the development of these techniques themselves was based on the assumption that atoms and molecules exist and have certain properties. One might reverse Atkins' statement without making it meaningless: we can see atoms and molecules because we know they exist.

3. DEMOKRITOS

The first corpuscular theory was launched by Demokritos about 2400 years before the pictures described above became available. The relevance of Demokritos' theory to modern science education is more apparent if one knows something about its origin. Demokritos participated in a debate among ancient Greek philosophers about the nature of change (Van Melsen, 1962). In this debate two opposite views were held. One, represented by Herakleitos, stated that change is the only reality in the universe. The permanence that we seem to observe in many objects around us is, in his view, merely a sensory illusion. As an example Herakleitos referred to a river, pointing out that although the river itself appears to us as a permanent object, the water is moving all the time and the river is never the same. His view was opposed by Parmenides who denied the very existence of change. In his opinion the world has always been and will always remain as it is now.

Parmenides and his followers found themselves confronted with the challenge to explain the observation of apparent changes which they claimed not to be real. Demokritos' atomic theory can be seen as an attempt to meet this challenge. Demokritos saw the universe as a three-dimensional space in which innumerable extremely small particles were engaged in an eternal motion. He called these particles 'atoms' and assumed them to be indivisible, immutable, invisibly small and of an infinite variety in shape and, below the limit of visibility, also in size. Demokritos claimed that every change that we observe in the world around us can be reduced to a change of position of atoms in space.

The idea of 'explaining away' an apparent change in this manner is still perceptible in modern science. This can be illustrated by explanations of chemical reactions, some of which present themselves as spectacular events, resulting in impressive changes in the properties of matter. Yet a chemist can explain easily that each of these reactions involves nothing more than a rearrangement of atoms in space.

It is intriguing to see an orange powder in a test tube disappear gradually on heating and silvery drops appear slowly near the mouth of the test tube. It is even more surprising that during this proces a glowing wood splint starts to burn brightly when kept in the mouth of the test tube since normally a glowing splint is extinguished when pushed into a test tube. But to the chemist all this is no mystery. It is simply:

$$2\,HgO \dashrightarrow 2\,Hg + O_2,$$

in other words: a rearrangement of mercury atoms and oxygen atoms in space. By balancing the equation we make sure that the number of atoms on the left and on the right is the same for each species. In other words: everything is still there. In a more advanced chemistry course the same process could be described as a rearrangement of atomic nuclei and electrons. The idea is the same and it is perfectly in line with the ambition nourished by Demokritos over two thousand years ago: to argue that change as we observe it in our environment does not effect objects themselves but only their position. The orange colour, the metallic lustre and the flaring of the wood splint are sensory illusions, the reality is a replacement of some invisibly small and unchanging objects in an empty space (for other examples see Meheut & Chomat, 1990).

Does the corpuscular description of chemical reactions offer an explanation that is worth while to teach? Children as well as adults are often satisfied with an explanation that reduces a mysterious phenomenon to a displacement of objects in space. If a magician conjures a rabbit out of his apparently empty hat we feel that the rabbit must have been hidden somewhere, either in the hat or in the magician's sleeve or somewhere else. We do not accept that the rabbit did not exist before the trick was performed and that it was created out of nothing by the magician. We prefer to believe, under normal conditions, in conservation of objects.

Object conservation is an important principle in our daily life. It is developed (Piaget, 1976) in early childhood when the child discovers that if, say, a red ball is put in a box and the box is closed and then reopened somewhat later, it will again contain a red ball. If the child is able to speak, it will say that this is the same ball, and that it was present all the time in the box when it was closed. This statement is not based on observation alone but also on the principle of object conservation. This principle helps us to create some order and even predictability in the world around us. The child will develop several other conservation principles like conservation of number (the number of objects in a collection is independent of the order in which they are counted) and maybe even conservation of energy. Together these conservation principles deliver the reassuring message that the appearance of change is often deceptive and that the world is in fact a rather reliable place to live in.

Object conservation is the first and most fundamental of these conservation principles. In a chemical reaction objects and even the substances from which they are made are not conserved. Explaining a chemical reaction in terms of a rearrangement of atoms or molecules in space is an attempt to make the principle of object conservation applicable to a large group of phenomena in which its applicability is not immediately recognized.

Does such an explanation help students to understand chemical phenomena? Does it satisfy their need to understand or even their need to get a grip on processes around them? The corpuscular explanation summarized in the equation leaves a few essential questions unanswered. What happens to the orange colour in the test tube? And why is the metal a liquid? In other words: the explanation of the chemical reaction as a rearrangement of atoms in space is consistent with the principle of object conservation but it raises questions regarding the relations between atoms and molecules on one side and observed phenomena on the other. 'Relating macroscopic phenomena to (the behaviour of) microscopic particles' is not the same as learning about microscopic particles. Much of the mystery of substances and their reactions remains unsolved even if one has learnt to balance the equation.

Nevertheless one might argue that every good explanation raises new questions and that even Demokritos himself left many questions unanswered. After all, he started a research programme rather than producing final answers.

4. MINIMA NATURALIA

Children tend to attribute all kinds of features of macroscopic systems to molecules or atoms. Ben Zvi (1986) found that children aged 15 assume copper atoms to be malleable like the metal itself. Research activities leading to the development of "Chemie in Duizend Vragen" (Chemistry in a Thousand Questions, De Vos, 1989) produced other examples, three of which will be mentioned here. Students involved in these examples are aged 14 or 15 and enjoy their first year of education in chemistry. For more information the reader is referred to De Vos and Verdonk (1987a) and De Vos (1985).

- Some students assume candle wax molecules to be soft: "A soft substance cannot consist of hard molecules".
- After an experiment on rust formation students working in small groups were asked to draw what they imagined to be a picture of a rust molecule. Some drew two adjacent circles representing an iron atom and an oxygen atom, but others drew one circle, labelled it "iron atom" and surrounded it by a brown ring of "rust".

- Having learnt that in hot water molecules move faster than in cold water, several students stubbornly persisted to talk about "hot molecules". When the teacher explained to them that molecules of hot water and cold water differ only in motion and that we experience this as a temperature difference, one group wrote in their report: "Molecules of hot water move faster, but they are cold inside."

Such ideas are clearly not part of accepted science. Nevertheless they may in some cases be encouraged or even inspired in an unintended way by elementary science textbooks. In a thought experiment used in some science courses molecules are introduced by asking students to imagine a drop of water (or a grain of sugar, or any other suitable object) being split into two pieces, one halve split again, etc., until at a certain moment, far beyond the limits of what is technically possible, no further splitting is to be imagined since, as the book states, the particles obtained in that way would no longer possess the properties of the original substance. The smallest particles that still possess the substance properties are then said to be molecules of that substance. Is it surprising that students believe a molecule of candle wax to be soft and a molecule of iron to be capable of covering itself with rust?

Other books present a straightforward definition of a molecule as "the smallest amount of a substance that still possesses all the properties of that substance". The authors of such a definition do not seem to be aware that substance properties include boiling point, melting point, solubility, malleability and many others that are not considered by scientists to be properties of molecules.

What is the scientific status of these naive ideas about molecules which seem so attractive and self-evident to children and which apparently are even capable of creeping into the minds of inattentive schoolbook authors? One could take the view that it is incorrect to attribute properties of macroscopic systems such as temperature and malleability to molecules or atoms. But things are not that simple. After all we do attribute mass to an atom and to a molecule. The mass of a water molecule is 3×10^{-23} g which is very small but not fundamentally different from the mass of a drop of water. And there are some other macroscopic properties which are also attributed to atoms, molecules and other 'microscopic' particles (See §6).

But there is more to it than just a few exceptions to a rule. The 'naive' ideas about molecules in twentieth century science education correspond almost exactly with particulate theories developed by some prominent medieval philosophers. Averroës, a Spanish-Arabic philosopher (1126 - 1198), commenting on Aristotle, suggests that each substance consists of smallest amounts named 'minima naturalia' (Dijksterhuis, 1975, II - 137) possessing all properties of the substance except its divisibility. In chemical processes Averroës assumes the minima naturalia of the reacting substances to interact and minima naturalia of the reaction products to appear one by one. Contrary to Demokritos' atomic theory (See §3) the reaction does not merely involve a change of the positions of atoms in space but a real internal change of the minima naturalia producing minima of a different nature.

The minima naturalia theory, which offered an alternative to Demokritos' atomic theory, flourished in fourteenth century Europe and was still accepted by several philosophers and scientists in later centuries. The supporters of the minima naturalia theory were very well aware of the fundamental difference between their ideas and Demokritos' atomic theory in which the atoms have no substance properties but are characterized by shape, size and motion only. And they did not aim, as Demokritos did, at 'explaining away' change.

Modern atomic theory resembles the ideas of Demokritos much closer than those of Averroës and his followers. But wouldn't Averroës' theory link up much better with intuitive ideas held by present-day children and therefore be much easier to teach? And isn't the definition in some of our schoolbooks of a molecule as the smallest amount of a substance that still possesses all its properties a far but clear echo of the minima naturalia theory?

5. THE NATURE OF DISSOLVED SUGAR

A, J and R, all aged 14 or 15, have carried out an experiment about the dissolution of sugar in water as part of a course in elementary chemistry. The experiment involving a sugar candy crystal hanging on a string in a bottle of water was performed at home by each student individually.

Back in school the students discussed questions which they had answered at home. They tried to reach agreement on their answers in order to hand in one set of group answers. Their discussion about these questions was recorded on audiotape. One of the questions is 2a: Has the amount of solid changed during the experiment?

J does not agree with A and R about how to answer this question. She asks the teacher (L) for help.

J: Sir, we don't agree.
L: Let me see. What's the problem?
J: They're saying it has changed and I say it hasn't.
L: Which question are you talking about?
J: About 2a.
L: "Has the amount of solid substance changed?" What solid substance was that?
A: The candy.
J: The sugar.
A: Yes.
R: And now she keeps saying that the amount of solid hasn't changed.
L: You did the experiment. How long did you leave that lump of candy hang in the water?
J: Quite some time.

L: And when you took it out again, had it changed by then?
J: Sure, it was almost finished.
L: It had become smaller. Also lighter, do you think?
J: Yes, of course.
L: (*To the others*:) And do you agree?
R: Yes, we do.
L: And that lump of candy was solid substance, wasn't it? The only solid substance in the bottle?
J: Yes.
L: And that has become smaller. Then what do you think about question 2a?
J: It stayed the same. But they keep saying ...
A: Become smaller of course.
(Silence)
L: And what do you think about the amount of liquid? Has that changed? That is question 2b.
J: No, that stays the same as well.
L: Suppose you look at the questions 2c and 2d first. Can you agree on them? If you try that first, then I'm sure you will succeed on 2a and 2b later
What do you think of 2c? (*Question 2c: Has the amount of sugar changed?*)
J: Yes, that hasn't changed, that's the same answer that they have.
R: No, the amount of sugar doesn't change and water doesn't either. That stays the same.
L: But the amount of solid sugar, does that stay the same too?
J: Yes, I think it does.
A: No, that's getting less.
R: That's what I think, it's getting less.
L: (*To J*:) But now look at the drawing you've made. That lump of candy. After some time it is smaller. What is now at those places where there was solid sugar first? If the outer layers of the lump have disappeared, what is then taking their place?
J: Well, eh ...
A: Water.
J: Yes, but that was somewhere else first, there isn't more of it.
L: Did you look at the level of the liquid in the bottle? To see if it had changed?
J: No, did we have to?
L: No, you didn't. But look. Suppose I show you a bottle after the experiment, when the candy has already been removed and the bottle has been shaken. Would you say that the bottle then contains liquid?
J: Yes.
L: And if you put sugar in your tea and you stir till you see no sugar any more, where then has the sugar gone?
J: It dissolves.

L: And that tea you get, with that sweet taste, would you call that a liquid?
J: The tea is a liquid all right ...
R: Yes, of course, that's what you drink, isn't it?
L: And is there still solid in that cup, after the sugar has dissolved completely?
J: I think there is.
L: You're calling that sugar a solid, even after it has dissolved.
R: But it isn't a solid at all any more, that's completely impossible!
J: I think it is, but they don't agree.
A: No, we think it's liquid.
L: Suppose you melt a piece of ice, then do you get a liquid?
J: Yes.
A: Yes.
J: Yes, but that's because of the heat, and the sugar doesn't melt, it just dissolves. The ice turns into water, but the sugar just remains sugar.
L: And sugar is a solid anyway.
J: Yes, of course.

In my interpretation this little conversation between a teacher and three students is in two ways a reversal of the situation that we tend to consider as 'normal'.

In the first place it seems that this time it is the teacher who is learning. It is clear that J's stubborn refusal to agree with her classmates is not just a form of obstruction. Neither does she seem to talk incoherent nonsense. The teacher, sensing that J expresses some alternative but probably consistent view, focuses most of his questions on her. Her answers are straightforward, matter-of-fact and mixed with some surprise about the failure of the others to agree with her. Finally she manages to make her view understood, at least by the teacher: dissolved sugar is still a solid.

The second reversal, as I see it, is in the transfer of properties. J's statement that dissolved sugar is a solid is not based on observation. She accepts that tea is a liquid and she does not claim that one can somehow feel or see little grains of solid sugar in the tea. Then where does her idea come from?

There is broad agreement among educational researchers that children tend to attribute all kinds of substance properties, such as colour and density, to individual 'molecules' of that substance. J may picture sugar molecules as little, solid objects and it is not unlikely that in her mind these sugar molecules resemble small grains of sugar in many respects. But it seems that she transfers the solid nature of sugar molecules back to the substance in the dissolved state. Contrary to observational evidence she insists that dissolved sugar is solid.

This is of course nothing more than my own interpretation. J herself doesn't say anything about molecules in this fragment. But I would like to hear of other cases in which students, possibly more explicitly, transfer properties back to substances which they first have attributed to molecules.

6. MACROSCOPY IN A MOLECULE

Imagining a water molecule not to be an extremely small drop of water but something else, raises the question: what are the criteria for preferring one description of a water molecule to any other description of it as long as it is not a description of an extremely small drop of water?

In answering this question it is important to realize that in science a description of a water molecule is not something that stands completely on its own. First of all, it can not be considered to be independent of descriptions of molecules of other substances. If we assume several substances to consist of molecules then these molecules, different from one another as they may be, must have some common features. And second, describing a molecule of a specific substance is not an isolated activity of an isolated scientist. The description has a function: it is meant to be used as a model in scientific research. A model is a tool in the hands of a scientist who designs it and uses it for explaining or even predicting phenomena on the macroscopic level. A water molecule is designed in such a way that it can explain certain properties of water.

Anyone who designs a model as a tool for a scientific explanation of phenomena has to obey rules. The most important of these rules was first formulated in the fourteenth century by William of Ockham. It states, translated into language of our time, that a model should not contain elements which are not necessary in the explanations it can provide. A model should be as simple as possible. The rule expresses a kind of economy principle: one should try to explain a maximum number of phenomena by making a minimum number of assumptions. This is sometimes called Ockham's razor as it shaves off anything that is not absolutely necessary. With this rule we can distinguish in principle between two or more descriptions of a water molecule: for explaining a given property or list of properties of water the simpler of two models should be preferred. This can only be in principle, since it is not immediately clear how to count the assumptions which form the elements of the explanation. Or should they be weighed?

All this concerns only the number of elements from which a model is built. It does not say anything about what types of assumptions are to be preferred. It does not prescribe which characteristics make a good model and which ones do not. In microscopic (or rather: corpuscular) models of matter the choice has been largely determined by the successful development of classical mechanics in the seventeenth century. Since then, several mechanistic models have been suggested in physics as well as in chemistry. Corpuscules were seen as small objects in a three dimensional space, each obeying the laws of mechanics in the same way as macroscopic objects do.

Paradoxically, the application of Ockham's rule has not led to simpler models in the sense that they are easier to understand. As more and more familiar aspects of macroscopic objects, such as colour and temperature, are being omitted from corpuscular models it becomes more and more difficult to picture such models. Modern quantum mechanical models are expressed in mathematical language and are not supposed to be 'pictured' by their users. Science teachers who want to start from children's own ideas therefore find themselves confronted with the problem of looking for a compromise somewhere between the naive ideas that secondary school students themselves appear to have (see §4) and very sophisticated models developed in quantum mechanics and nuclear physics.

Looking for this compromise in secondary school textbooks on physics and chemistry in the Netherlands and in some other countries, I found five aspects of our macroscopic world which usually are attributed to the corpuscular world. One of these, mass, has been mentioned in §4. A water molecule has a mass just like any macroscopic object.

But in schoolbooks a water molecule is also, albeit implicitly in most cases, situated in space and time like any macroscopic object. The validity of our time concept on the corpuscular level is important since it is related to our view on causality. The location in three-dimensional space is made explicit when the optical activity of organic compounds is explained by pointing out that two molecules can be each other's mirror image if they do not possess an internal plane of symmetry. This is in agreement with the suggestion made in 1874 by Van 't Hoff to extend the accepted structural formula as of organic substances to three dimensions.

Apart from mass, space and time, two other aspects of our macroscopic world are used in descriptions of corpuscular models in school books. These are energy and electric charge. For energy there are some restrictions: not all forms in which energy can manifest itself at the macroscopic level are allowed in corpuscular models. Kinetic energy is accepted and so is potential energy but heat and sound are reduced to kinetic energy of molecules. The energy concept in corpuscular models is essentially mechanistic in nature.

Electric charge as an aspect of corpuscular models is introduced in physics lessons when an electric current is described as a stream of electrons and a positive or negative charge on an object as a shortage or surplus of electrons. In upper secondary school an atom is said to consist of a positive nucleus surrounded by a number of negatively charged electrons. Apparently these particles attract and repel each other in the same way as charged macroscopic objects do. The electron concept implies that electric charge is available in certain minimum quantities only. In other words: electric charge is quantized in these models. Both mass and, in more advanced courses, energy are also quantized. Space and time, however, are presented as continuous in corpuscular models used in secondary schools.

Using mass, space, time, energy and electric charge as elements in building a corpuscular model of matter means that these five phenomena themselves can never be explained by such a model. But the model can be useful in explaining other aspects like temperature, colour, conductivity and the formation of chemical bonds. Schoolbooks on physics and chemistry do indeed offer such explanations.

All this seems to offer a possibility to teach corpuscular models in a rather consistent manner. But is it also consistent with what we know about the way students reason and observe? There seem to be at least two nasty questions waiting to be answered. First: do students spontaneously and intuitively accept and apply Ockham's rule? From what we know now, we must assume that they do not. And second: if they did, or if it were successfully taught as a rule, would it be obvious to students why the elements from which a corpuscular model is to be built, should be mass, space, time, energy and electric charge? Or would they prefer to choose, say, colour, taste, toxicity, temperature or malleability? In other words: what criteria can we offer to students for determining from which elements a scientific model of matter is to be built?

7. MOLECULAR SPECIES

Is alcohol in wine a pure substance or is it a mixture? In many textbooks on elementary chemistry the term 'substance' is first introduced in a provisional manner which includes mixtures as well as pure substances: air and wine are not distinguished immediately from alcohol and water. Somewhat later a distinction is made between mixtures and so-called 'pure' substances. Air and wine are said to be mixtures, while alcohol and water are pure substances.

This distinction raises two mutually related questions:

- What are the criteria for 'purity'?
- How do we tell pure substances from mixtures in practice?

The chemical criteria for purity are ambiguous. On the one hand, the adjective 'pure' refers to a product obtained by repeatedly applying purification techniques to some raw material. The product is said to be a pure substance if it exhibits a constant boiling point and other physical constants that are in agreement with values tabulated in official documents. This distinguishes a pure substance from a crude product which, in general, possesses another set of physical constants than tabulated for pure substances.

On the other hand, however, a pure substance is often considered to be an unattainable ideal. One hundred percent pure water does not exist, it is a theoretical concept like the ideal gas. This implies that in practice there are only mixtures. Which of these two pure substance concepts should be taught? But the problem is even more complicated.

Distinguishing between pure substances and mixtures does not take into consideration the possibility of using a substance name to refer to a component of a mixture. Yet in professional chemistry as well as in daily life it is very common to talk about a substance as a component of a mixture. That is why the introductory question above is so confusing. Consequently, it is not sufficient to present 'alcohol' as a name of a pure substance, characterized by a set of substance properties including boiling point, density, refraction index etc. Alcohol in wine does not exhibit the properties of pure alcohol. Wine has its own set of 'mixture properties' which does not include the properties of each of the composing substances. How can this be taken into account in teaching a substance concept in elementary chemistry?

Listening to chemists one gets the impression that their substance concept is strongly influenced by corpuscular notions. Alcohol is not just a colourless liquid, it is also CH_3CH_2OH, i.e. a molecule or rather a molecular species. Molecules of this species exist in wine as well as in 'pure' alcohol and the properties of alcohol are the properties caused by molecules of that species.

From an educational point of view this interpretation of the substance concept opens up a possibility to develop the chemical substance concept simultaneously on the macro and on the micro level. In this approach matter is considered to consist of 'molecules'. The concept on the corpuscular level corresponding to substance however is not molecule but 'molecular species'. Just like the word 'substance' does not indicate a certain amount, the term 'molecular species' does not refer to a certain number of molecules. Wine is said to consist of molecules of different species; one of these species is called 'alcoholmolecule' and it corresponds to the substance called alcohol.

In biology individual animals, plants or other entities belonging to the same species are not identical in every respect. Two apples can exhibit several differences, even if both are golden rennets. The chemical substance concept, however, requires all molecules of the same species to be completely identical. This is just as theoretical as the purity concept mentioned above, not only because molecules are too small to be seen but also because we have no macroscopic analogue. Identical objects do not exist in our macroscopic world.

It is important for students to understand that all molecules of one species are identical, that there are no smaller water molecules and bigger ones and that molecules do not exhibit scratches or marks like for instance two coins of the same value do. In struggling with this problem (De Vos & Verdonk, 1987a,b) we felt the need for a noun that could refer to the phenomenon of two or more objects being identical. 'Identity' is not acceptable since it refers to one object only: a person preserves his or her identity through a period of time in spite of growing older. In communicating with teachers, curriculum developers and educational researchers about identical objects we found it convenient to use the word 'identicity' (in Dutch: identiciteit). We can now refer to the identicity of molecules belonging to the same species.

This may make communication easier but it does not, of course, solve the problem of how to establish the identicity of individual objects, especially when these objects are molecules. Neither does it tell how to teach the concepts of substance and molecular species simultaneously. For macroscopic objects we introduced (De Vos, 1989) the rule that two objects are identical if they do not exhibit any difference except in position and in movement. These exceptions are obvious: two objects always differ with respect to their position in space and it does not matter in which direction they move or rotate. The key question for the identicity of two macroscopic objects is: if someone secretly exchanged them, would you be able to find out?

With molecules the criteria are the same as for macroscopic objects, but since we cannot see and manipulate individual molecules, the application of the criteria is founded on attribution instead of on direct observation. Students involved in learning chemistry along these lines require a certain degree of freedom to make and discuss their own decisions provided they learn to be aware of the tentative character of decision making on these hypothetical grounds. In our research project most students agreed that water molecules and ice molecules belong to the same species, while rust molecules and iron molecules do not. This provides a basis for a definition of a chemical reaction on the corpuscular level: if the molecules before and after a process evidently do not belong to the same molecular species, the process is a chemical reaction.

It is interesting to compare the relationship between substance and molecular species to the relationship between element and its corpuscular counterpart, which is not atom but atomic species. Each element corresponds to a certain type of atom, characterized by its nuclear charge (which avoids the problem of isotopes). But not all atoms belonging to the same species are identical: copper ions differ from copper atoms. However, atoms, unlike molecules, preserve their identity throughout a chemical reaction. Whereas identicity is the important concept for molecules, identity is essential for atoms.

8. HOW TO TEACH MOLECULES

Working on "Chemistry in a Thousand Questions" I have arrived at a few conclusions which are relevant to the topic of the seminar. I will mention one which I consider to be the most fundamental.

In science lessons at lower secondary school level it is not very important which corpuscular model a child learns. It is much more important to preserve something of the uncertainty and the tentativeness that are characteristic of models. This does not mean that a scientific theory of model development and model application in science is to be taught to young children. It means that children should experience how it feels to work with ideas without being sure whether they are correct or not. Working with models is not just an intellectual affair but also an emotional one. It requires creativity as much as discipline and it may lead to frustration as well as to satisfaction. This way of learning to work with models is encouraged if the teacher does not present corpuscular models as facts discovered by famous scientists but instead asks students about their own ideas, stimulating them to discuss these and to test their consequences in suitable experiments.

As an outcome of elementary science education I would prefer a child thinking that a copper atom is malleable but feeling a little uneasy about it to the same child knowing for sure that a copper atom is not malleable.

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AN APPROACH TO THE EDUCATIONAL PROBLEM OF INTRODUCING THE DISCONTINUUM CONCEPT IN SECONDARY CHEMISTRY TEACHING AND AN ATTEMPTED SOLUTION

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1. INTRODUCTION

Yet during my time as a student teacher I was interested in the question: What do people understand by what I say? (incidentally, my interest was not caused by my teacher training). Consequently my lesson planning was always determined by understanding difficulties which I had observed before and more by educational goals than by those relating to the subject matter of my lessons (Dierks, 1965). This attitude coincided first with some of J. Weninger's concepts, and later also with those of H. Pfundt (Dierks, 1988) during the development of the IPN course on "Substances and the Conversion of Substances". Much emphasis was placed on the selection of words and formulations for the course description, so that it could also be understood by pupils as immediately as possible without recourse to definitions. In order to be able to do this it was necessary to establish what imaginations and associations would be evoked by the acoustic and visual phenomena used - in this case statements and texts related to experiments.

W. Jung's sceptical comment about the usefulness of lists of pupils' concepts prompted me to search for ways of dealing with undesirable concepts so as to achieve the desired progress despite difficulties. I found a clue in a quotation in which M. Pope and J. Gilbert refer to G.A. Kelly:

"For Kelly, successful communication between people depends not so much on commonality of construct systems, but upon the extent to which people can "construe the construct system of the other"".

The question of whether understanding between those involved is possible in lessons is clearly a social rather than a cognitive question, namely that of whether each of those involved wants to listen, and if he/she wants to listen, how he/she should behave.

Part of the answer to the cognitive part of the question should be allowing a cognitive conflict to occur. Empirical investigation showed, however, that this did not seem to be reliable or that influences which were not considered during the answering process interfered with the development of conflicts. This further clarified the meaning of Kelly's hypotheses for me.

All in all, understanding in chemistry lessons seems to me to be a communicative problem. This is why I believe that "research in chemical education is concerned with problems of *communicating* facts which are researched by the discipline, and the techniques and results of research".

2. ONE PART OF THE ATTEMPTED SOLUTION

I construct my concept of events in such a way as to enable me to use it successfully for my ends.
In his book "The Reflective Practitioner" (1983) D.A. Schön writes: "When a practitioner makes sense of a situation he perceives to be unique he sees it as something already present in his repertoire". This is not only true of the practitioner but of everybody who is interested in an event. Kelly describes this process as the grouping of earlier impressions which are regarded as similar in some respect. Schön emphasises the metaphorical character of the classification which often characterises our descriptions of uncommon events.

I assume that pupils are basically familiar with all the images that we teachers use metaphorically to explain chemical processes. However, they often associate the phenomena which we use to explain experiments with different things than we do. Their interest in the processes (their point of view or approach) is not consistent with ours; they think of a different use than we do. We should not consider this to be strange - it is not so long ago since we were interested in "extremely white" clothes, bread rolls, and paper and were also able to produce them (from a technical point of view); at that time we were not interested in the consequences, although we ought to have been able to foresee them. Indeed, while others were already considering the consequences, some of us may have retained our interest and habits despite our recognition that these were untenable. Pupils are disadvantaged in the learning situation insofar as they do not possess such an insight (in contrast to the above example). They must be taught this first. The aspect which is alien to them can hardly be perceived by them as one of the two between which we try to construct a cognitive conflict. Apparently people are only aware of a conflict if they consider both of the various approaches to be feasible.

In the IPN course, for example, sulfur was burned. Although the pupils talked about "burned sulphur" when describing the experiment, none of them was convinced that the acrid gas produced might still be sulphur or contain sulphur. In this situation clearly "burned" does not mean that a new characteristic has been acquired but what has happened to the sulphur. The desire to refer to sulphur dioxide "more correctly" in this situation by the symbol SO_2 cannot be understood. This symbol originates form the concept of the "conservation (of atoms)". Pupils associate "disappearing/destroying" with burning, as one is usually interested in making use of the combustion of candles, wood, petrol, or oil rather than considering the invisible products of combustion. The course makes use of this concept not to cause a confrontation between everyday and specialist concepts, but merely to confirm the fact that in processes which interest chemists, things and that bundle of characteristics which is referred to as matter disappear and new things with different characteristics come into existence. The fact that substances do not disappear irrevocably during a chemical process, and that these processes can also be thought of in terms of "conservation" must be explained with the help of other phenomena.

The "cognitive conflict" referred to does not seem to occur in the situation described because only familiar associations are considered to be possible. However, we are definitely used to associating one impression relating to an event with various groups of other impressions according to our interests, and seeing things or events from different points of view or approaching them differently. The more numerous our possibilities in classifying an impression, the more complex our imagination of a fact can be. If I drive my car, clean it, make sure that it is safe, protect it from rust, have it repaired, make sure that it cannot be broken into, and argue about its resale value, each action is carried out for a different reason (even if some are more closely related than others and therefore seem to be part of the same reason). Interested in these we find it difficult to accept an additional unfamiliar consideration like that of environmental protection, for example; in some cases it is not considered at all. If such a consideration is accepted and if one wishes to act in accordance with this - in consequence by having a catalytic converter fitted and by being able to use unleaded petrol - a conflict may be produced. In addition to this, we are not always immediately completely aware of these complexes.

Usually one of the possible classifications is chosen according to habit, or the situation, or due to a striking phenomenon or past impressions. We automatically reduce the complex of what can be perceived to that which interests us at the present time. We often consider it to be a matter of course to see an issue in one way rather than another even if this is not the only possible way of seeing it.

3. ANOTHER PART OF THE ATTEMPTED SOLUTION

Comparing my concepts with those of the people with whom I wish to work

What I have said so far could make teachers despair, especially if they take the epistemological insights of the more radical of the constructivistic epistemologists, namely that each of us constructs his/her own picture of the events around us due to his/her interest, and that each of us constructs them in a different way. In this case communication and learning about concepts which are alien to one would be impossible since people's interests vary. (This assessment is not erroneous if one considers the behaviour of some people who are mentally ill.) We should always remember this if unusual approaches are to be introduced in lessons. The phenomena introduced are classified according to interest the minute they are perceived - usually differently to the way we classify them.

Daily life does, however, provide some encouragement. In addition to the desire to act successfully on my own I sometimes also have the desire to work successfully with others. In such cases I construct an imagination of the behaviour I expect from the others on the basis of past observations - Kelly's statement; these are, however, always based on my conceptions, on how I usually classify things and events. The less I am used to remembering that it is possible to classify things in different ways, not just in a spontaneous, situation related fashion, the slighter is my chance of abandoning my point of view, following a different kind of interest, and seeing the issue in a different way: in short, the smaller is my chance of understanding what the other person means - my chance of "construing the construct system of the other".

Normal teaching - at least in scientific subjects - does not demand being flexible concerning the classification of perceptions; it does not consider the need to the able to communicate. The IPN course does consider this e.g. by carrying out an experiment in which burning and slaking of lime can be seen as a process of "breaking down and combining" and in which these concepts - that one can combine that which has been broken down and vice versa - can be applied to the melting of ores and the incinerating of metals. Pupils can now observe a conflict because they have acquired two different points of view in the meantime. Should a chemical process be seen as something which makes certain characteristics of the substances used (e.g. iron, oxygen) disappear and produces different things with different characteristics (the products, e.g. blue-grey ash), or as a process by which the names of the products formed (e.g. iron oxide) indicate the substances which were used to produce them or which were formed when the substances were broken down? Now pupils can become aware of the fact that it is not unusual to ask more than one question in relation to an issue (in this case a chemical reaction), that one can see one and the same thing in more than one way and according to various different interests. With hindsight they can see that this depends on the approach taken. From now on they are better able to cope if they are presented with interpretations based on approaches whose relation to the issue at hand is unclear. They can ask about what has caused other people to adopt different interests and concepts instead for asking "why?", which usually leads to an undesired logical reconstruction of conclusions. They can provisionally accept the alien point of view and decide on the suitability of different approaches for themselves. Up to now they were dependent on imitating or rejecting instead of constructing.

Only once pupils consider the classification of (so-called chemical) procedures as "conservation" to be useful - in relation to the products formed - can they see that something is preserved but not the substances which were there at the outset. At this stage of considering what might be preserved we decided not to speak of elements and compounds to but to replace the description of the continuum, of substances and things with that of the discontinuum, of atoms and molecules - more generally henades -, aggregates and their structures. This is not primarily an acknowledgement of modern scientific concepts - the concept of conservation forms part of the understanding of mechanical procedures, and this in turn is related to concepts which are the product of the observation of discrete things.

In the IPN course it was attempted to describe what was meant as exactly as possible in accordance with the concepts of the pupils i.e. one thing was described in various different ways according to various concepts, each time with the words which are associated with the concepts and the related images. If chemical procedures (e.g. the synthesis of water) are associated with the concepts of "disappearing/nascent" and "material continuum" they will be described in one way (e.g. if hydrogen and oxygen are burned water is produced), and if they are associated with the concepts of "conservation" and "submicroscopic discontinuum" they will be described differently (e.g. the atoms of an H_2 and an O_2 aggregate are rearranged to form an H_2O aggregate). It is possible to refer to water as hydrogenoxide because it is formed from hydrogen and oxygen and because these substances can, in theory, be formed again from water. Speaking of substances one cannot, however, say that water consists of hydrogen and oxygen, as their properties can no longer be discerned. To retain the distinction between the names of substances and units according to their classification, "chemical formulas" and symbols are only used to refer to henades in connexion with the discontinuum concept. One and the same thing is referred to by various different descriptions or names according to the way in which it is approached.

Continuum Concept	Discontinuum Concept
portion of substance (18 g water)	aggregate of henades (1 hen H_2O l)
substance (water)	aggregate structure (H_2O l)

(1 hen = $6,...10^{23}$)

The attempt to describe what is meant as appropriately as possible is based on the observation that imaginations and the groups of words associated with them are extremely closely linked; and that it is extremely difficult to dissociate a word from a imagination once it has been associated with it (not only for oneself) and to link it with a different concept, especially if a common use is to be varied. The words "to split", "to divide", "part", "particle" which are often used when introducing the concept of the atom from the starting point of the continuum concept, evoke such an unsuitable picture from the specialist point of view (the meaning of the word "atom": "that which cannot be cut" clearly indicates this). If a big yellow piece of sulfur is cut into smaller and smaller pieces why is it that the sulfur atoms are not yellow? Why is it that mercury atoms are not liquid and water molecules are not wet?

The IPN course sets out from the concepts of composition and decomposition and from the observation that that which is preserved cannot possess those properties characteristic of substances, but that these come about by the processes of composing and therefore also disappear by decomposing. (The epistemological term is component rather than part.) The affiliated concept of construction is used together with the idea that the bricks of a house do not possess the qualities of a house. This image also makes it easier to accept the fact that atoms are always present in the aggregates - like the bricks in a house - and are not produced by splitting. The discrete existence of the atoms, molecules, ions, and other "submicroscopic entities" is referred to with hindsight as "henade" instead of "particle".

In conclusion I should like to remind people of the following: the initial approach concerning the use of scientific concepts described here takes both psychological conditions and the social requirements of developing the ability to communicate and to think in a complex manner into consideration. In order to fulfil the last condition it is also necessary to include value judgements such as those in STS teaching. This was not dealt with in this paper.

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MACRO-MICRO RELATIONSHIPS: A KEY TO THE WORLD OF CHEMISTRY

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1. INTRODUCTION

There is an accumulating body of research data which shows, in different scientific domains, that there is a gap between students' mental pictures of various scientific concepts and the scientist's understanding of the same concepts. It seems that very often students start their studies with well rooted ideas based either on intuition or on previous learning and distort new information so that it will fit into their existing framework. It is essential to study these mental pictures in order to understand student difficulties and try to develop methods that would foster a sound understanding of scientific concepts. In particular, it is important to study the mental pictures of basis concepts formed by students at an early stage of their studies, since misunderstanding of such concepts may prevent meaningful learning at later stages.

The atomic molecular model plays a central role in the study of chemistry and is usually introduced very early in the curriculum. The root of many difficulties that beginning chemistry students have, appears to lie in deficient understanding of the very basis concepts of the atomic model and how it is used to explain phenomenology and the laws of chemistry.

The proper understanding of chemistry requires that students be able, from the beginning, to function at several levels of description. For example, when the teacher writes a chemical formula on the blackboard, e.g. $H_2O_{(l)}$ or $H_{2(g)}$, students are expected to function simultaneously at three levels:

a. the macro, phenomenological level - the difference between the properties of a liquid and gas;
b. the atomic molecular level - the bonding of atoms within a molecule of H_2O of H_2;
c. the multi-atomic level - the idea that even a small drop of water consists of many molecules with a certain organization, and each of them has some internal structure.

Similarly, when studying aspects of energy changes accompanying chemical changes, students are expected to be able to explain the phenomenology-temperature changes - by the use of appropriate models. These models should deal with two aspects:

a. The link between energy transfer and temperature change.
b. The link between molecular model and energy transfer.

In the present article we would like to review some of the difficulties students have in understanding macro-micro relationships. We would also like to point out, how some of these difficulties may be overcome by appropriate attention to teaching methods.
The article will consist of three parts:

a. A summary of data which was published elsewhere presenting difficulties that students have linking properties of materials and the nature of chemical reactions with the atomic-molecular models. We will also mention attempts made in order to develop "correct" models in the student's minds.
b. Problems which students have with the links between chemical reactions, energy transfer and temperature changes.
c. Description of an attempt to help students overcome the problems presented in section b, and first results of examining whether this attempt was successful.

2. PROBLEMS CONCERNING MACRO-MICRO RELATIONSHIPS IN THE AREA OF STRUCTURE AND REACTION IN CHEMISTRY[1]

The study of students misconceptions in the relationship between properties and models had three main objectives: finding out how students visualize atoms, what models they use to represent elements and compounds and their visualization of chemical reactions.

Students' views about atoms

A sample of 288 students who had studies chemistry for about half a year participated in this study. The students studied in the 10th grade and their ages were about 15 years.

The students were given a questionnaire which consisted of several questions, one of which dealt with the concept of the atom. An experiment was described where a metallic wire was heated in an evacuated vessel until evaporation and a few properties of the solid and the gas were given, e.g. the solid conducts electricity, the gas is compressible.

The results of the analysis of students answers is presented in table 1. As can be seen, almost half of our sample claimed that the atom "isolated" from the solid had all the properties of the gas. Only about 15% of the sample understood that an atom cannot be regarded as a small piece of the substance which carries all the properties of the substance.

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1. Studies reported in this section were done in collaboration with B. Eylon form the Department of Science Teaching in the Weismann Institute of Science.

Table 1 Distribution of the "Properties" attributed to the Atom (N=288)

	"Origin" of the Atom		Properties	%
I	Solid	⟶	Solid	41.3
	Gas	⟶	Gas	
II	Solid }	⟶	{ + Solid	4.9
	Gas		Gas	
III	Solid }	⟶	Some of solid	25.0
	Gas	⟶	Some of Gas	
IV	Solid	⟶	Gas	4.2
	Gas			
V	Solid }	⟶	None*	14.9
	Gas			
VI	Unclassified			9.7

* Under this category are classified answers such as "it is impossible to isolate one atom" or "the properties mentioned are manifested by clusters of atoms".

Students views about solids, liquids and gases

The students were given the following symbols:
a. $Cu_{(s)}$; b. $H_2O_{(l)}$; c. $O_{2(g)}$ (or $Cl_{2(g)}$). They were asked to describe, using words, drawings and models what these symbols mean to them. The answer were read and analysed.

On the whole it seemed that students in our sample were acquainted with the symbols O_2, H_2O etc. More than 90% of them presented some sort of a model for the liquid or the gas while only 45% did so for the solid. The majority of the students gave some macro properties for water, together with the model while not as many described any properties of the gas.

It seemed that students were able to function both on the phenomenological and the model levels. The main question, of course, is what sort of models do they use in order to explain the phenomenology. Table 2 summarizes the distribution of the three levels of description for the liquid and gas questions. As is apparent from the table, only 8.4% of the students presented a multi-atomic picture both for the liquid and the gas. 64.5% of our sample presented a picture which led us to believe that they may see, in the notation $H_2O_{(1)}$ or $O_{2(g)}$, a representation of one particle only. To them, the use of (l) or (g) did not seem to mean that a multitude of molecules is indicated. This result may be caused by translation difficulties, but may be also due to conceptual misunderstanding.

One of the most surprising findings was the fact that after about six month of studying chemistry, many students in our sample had in mind (or rather on paper) an incorrect picture of the structure of a molecule

Table 2 Distribution of Description Levels Used by Students (N=248)
(Numbers indicate percent out of total sample)

Liquid \ Gas	Phenomology	Single unit	Many units	Total
Phenomenology	2.0	4.5	1.6	8.1
Single unit	4.5	64.5	10.2	79.2
Many units	0.4	3.3	8.4	12.1
Total	6.9	72.3	20.2	

and of the nature of chemical processes. The following examples may serve to illustrate these misconceptions.

- "Water consists of hydrogen, a molecule which appears in nature, and of oxygen".
- "Water is a compound made up of hydrogen, which in the gaseous state consists of two atoms, and also of oxygen". (This was accompanied by a drawing showing a diatomic molecule of hydrogen and at some distance an atom of oxygen.)
- "A water molecule which consists of an oxygen atom (O) and two hydrogen atoms (H_2) in the liquid state: $H_{2(g)} + O_{(g)} \longrightarrow H_2O_{(l)}$".
- "H_2 is hydrogen gas, O is oxygen; both appear in the aqueous state and form water".

From the data collected we could be fairly sure that about 70% of our sample knew that in a water molecule two hydrogen atoms are linked to the oxygen atom. The others seemed to hold a view, which we termed the "glue model", namely that a water molecule contains an entity of H_2. Such a view of the structure of a compound is congruent with the idea that during a chemical reaction the fragments are glued to each other, an additive view volunteered by some students (see for example, the third quotation above).

Students' responses supported the misconception regarding the nature of the atom described above. More than a quarter of our sample wrote sentences similar to the following:

- "$Cu_{(s)}$ is one atom of copper in the solid state".
- "$H_2O_{(l)}$ is a molecule of water in the liquid state".
- "$Cl_{2(g)}$ is two atoms of chlorine in the gaseous state".
- "At room temperature the chlorine molecule is in the gaseous state".

Some even went further and claimed that:

- "$Cl_{2(g)}$ is a diatomic molecule which has an irritating smell"
- "$Cl_{2(g)}$ is one molecule which has a yellow colour".

This seems to indicate that our assumption that students may retain, for a long period of time, the intuitive model of an atom as being a small fragment of the substance, may be true. If indeed, this is the case, it seems quite natural that in the minds of these students, a compound is viewed in an additive rather than in an interactive manner.

The results presented above were verified in other questions posed to the students. For example, about a quarter of the students presented models for the compound N_2O_4 which consisted distinctly of two parts namely N_2 and O_4. Only 10% could distinguish correctly between the symbols $O_{2(g)}$; O_2 and 2O. Of the 20% who presented $O_{2(g)}$ as one entity, many variations were apparent. For example, while one molecule of oxygen was presented by two circles put together, $O_{2(g)}$ was represented by two circles far apart.

Students' view about chemical reactions

The results presented in the previous section show that many students do not conceive a molecule of a compound as a new entity but rather as a mixture or glue of its constituents (the atomic molecular level). Also, students have problems to functions correctly in the multiatomic level of description. Other results, not presented here, indicated also that when asked to synthesize both levels (i.e. to present $Cl_2O_{(g)}$ as many molecules each with its correct internal structure) the performance of students dropped even further.

Yet, for a good understanding of chemistry, students must be able to function in this complex situation. For example, to understand correctly the difference between states of matter one must think about many molecules. Considering only one molecule may lead the student to conceive the difference between a gas and a solid as a difference in the structure of the molecule. Similarly, to understand correctly what a chemical reaction means, one must consider many molecules and conceive correctly the structure of each molecule.

In this section, we shall see that the consideration of single entities and a distorted picture of the structure of these entities is manifested in wrong representations of chemical reactions.

One question in the questionnaire dealt with chemical reactions. Students were told about two elements each having diatomic molecules - N_2 and O_2. They were given a list of possible products of reactions between the two elements (N_2O_2; NO; NO_2; N_2O_5; N_2O + NO_2; N_2 + O_2) and were asked whether, in their opinion, these products can be formed. Whatever their answers were, they were asked to explain them.

Students' explanations suggest two main reasons for the incorrect understanding of chemical reactions. One is that students do not consider the fact that many molecules take part in the reaction and concentrate on the single entities specified; namely one molecule of N_2 and one molecule of O_2. A few examples will illustrate this:

- NO_2 together with N_2O - No, wherefrom did we get another N and another O?
- N_2O_5 - No, the given elements were N_2 and O_2. Therefore , how is it possible that the product will have three additional oxygen atoms?
- NO - No, according to the law of conservation of mass, the mass of the product is less and not conserved and that is against the law.

- NO_2 - Yes, it is possible that nitrogen, for some reason and because of the reaction, will disappear within the vessel.

The second reason for the incorrect answers seems to be a wrong idea that students have as to what happens in a chemical reaction. Instead of conceptualizing the reaction as a process of bond breaking and bond formation, these students think that in a synthesis reaction the reactants become glued together. The following quotations from students' explanations are illustrative:

- N_2O - Yes, because the substance is made up of the two elements (for example water, H_2O can be dissociated into H_2 and O).
- NO - No, such a substance cannot be formed because the O at the beginning was O_2 and it cannot be decomposed. The N was N_2, it also cannot be decomposed.
- N_2O_5 - No, because these are not the elements we had. We did not have at the beginning $N_2 + O_5$.

Another fact which suggests that students do not conceptualize correctly chemical reactions is that more than a third of the sample did not distinguish between N_2O_2 and $N_2 + O_2$ and claimed that they are similar. About 9% of the students wrote that in both cases there was no reaction, while 31% argued that there *was* a reaction but that $N_2 + O_2$ is an alternative representation of the N_2O_2. This again shows that these students "see" a chemical reaction as a process of "gluing" the reactants to each other. Such a view would lead to a wrong mental picture of a compound as made up of fragments.

A curriculum designed to help students to overcome their difficulties

We can summarize the main lessons for students' difficulties as follows:

1. *An incorrect understanding of the atomic model.* If students feel that the atom is a small piece of an element, than an additive view of the structure of a compound (i.e. one small piece of one element being glued to a small piece of another element) is a natural outcome.
2. *Misleading use of models.* In textbooks, the use of models is usually confined to single entities. For example, the representation of a chemical reaction, i.e. the synthesis of HCl, includes one molecule of hydrogen, one molecule of chlorine and two molecules of hydrogen chloride.
3. *Misunderstanding of chemical equations.* The chemical equation is read by students as representing entities and not moles of entities.
4. *Information overload.* Our results show that when students have to represent a compound in the gaseous state their performance drops noticeably. In order to perform correctly, students have to coordinate two aspects, each of which causes difficulties by itself, one - the transition from an element to a compound and the other - the transition from one molecule to many molecules. The demands of the task apparently overload students' working memory and they regress to simpler, incorrect models by neglecting one aspect or another (Eylon, Ben-Zvi & Silberstein, 1987).

5. *Understanding the nature of chemical reactions.* This, of course, is by necessity, hindered by the incorrect understanding of structure.

In order to try and overcome these difficulties, a new program "Chemistry - a challenge" (Ben-Zvi & Silberstein, 1984) was developed, which adopted a historical approach. The atom was presented as a dynamic model which was developed and/or replaced according to current need for explanations. The expectation of the authors was that this approach would lead to a less concrete view of the atom. Also, much stress is put on presenting many particles whenever possible (models of solids, liquids and gases). Whenever the representation of many particles tends to obscure the point under discussion, the student is specifically told that for reasons of clarity we represent only one set of particles. Almost each chapter is followed by a unit called "the chemists' language", where the meaning of symbols and equations is taught, and here again the need to think simultaneously of many particles is stressed. It is our belief that if students will get used to thinking of many particles and also of the structure of each particle, then these aspects will become automatic and the more complex situations will not cause a memory overload.

As to the representation of chemical reactions, in the book we refrained from using "static" models of reactions (i.e. presenting the formation of sodium chloride as a transfer of an electron from the chlorine atom to the sodium atom). The first reaction discussed in depth is the electrolysis of sodium chloride and the approach used was that presented by Pauling in his "General Chemistry" book (1959). Students are made aware of the fact that in the molten salt there are many ions, that the ions move towards the electrodes and that the products are many molecules of chlorine and many "atoms" of metallic sodium. All other reactions are dealt with in a similar way.

A comparative evaluation of this program was carried out and the results show that in all aspects discussed above students performed better after studying this program (Ben-Zvi, Eylon & Silberstein, 1986a).

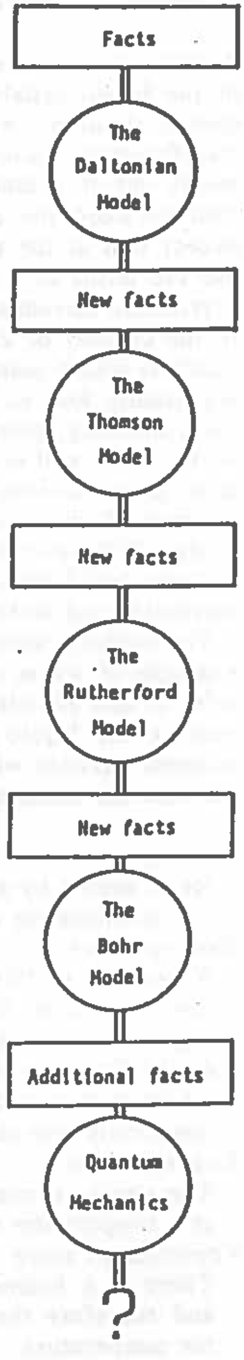

Fig. 1 Development of the atomic model in the new curriculum.

3. ENERGY AND CHEMICAL REACTIONS

Relating temperature changes to energy transfer

In the Israeli syllabus energy is the main topic for the 9th grade science classes. Students are supposed to learn about forms of energy, energy transformations and energy conservation. More than 10% of the time (4-6 weeks out of a total of 30 per academic year) is devoted to the distinction between the concepts heat and temperature. Therefore, one could expect that at the middle of the 11th grade, the students will be able to use the terms in a more or less correct way. This was the assumption of curriculum developers in the past and the two concepts were used freely in the chapter of chemical energy. What was not taken into account is a problem which seems to be specific to the Israeli scenery. In Hebrew you are usually told to "measure your heat" when you run a fever. You also hear, morning, noon and evening, that the "degrees of heat" in Jerusalem or Tel-Aviv will be so and so. Had we thought about this before, it would have been obvious that in the conflict between school and media, the "degrees of heat" would win the fight. This notion was confirmed in a study which involved 160 students from nine 11th grade classes. All the students had finished studying the topic of chemical energy according to currently used textbooks.

The students were given a graph showing the changes in temperature of a sample of ice as a result of the addition of energy. The students had to refer to and explain each of the various stages - heating the ice, melting, heating the liquid, vaporization and heating the vapour. A sample of students answers will serve to illustrate the confusion, in students' minds, between the terms energy (heat) and temperature.

Heating ice
- Ice is heated by adding more and more temperature.
- The temperature rises and because of this the process is exothermic.

Heating water
- A point C (0 °C) we have water in the liquid state and as a result of the temperature rise it absorbs energy up to point D (100 °C).
- Vaporization of the liquid by the addition of temperature. The molecules of the liquid decompose and change into separate atoms - the energy of which is higher than that of the molecules. The structure decomposed completely and changed into a gas.

Heating vapour
- The energy accumulated plus the energy added at this stage is released as a temperature rise in the system.

Vaporization stage
- There is a balance. At this temperature all the water has evaporated and therefore there will not be any change because we did not raise the temperature.

As we mentioned above, the students had studied textbooks that were written without the specific notion of possible misconceptions. These students performed well in standard achievement tests and the fact that they had basic problems of understanding escaped their teachers.

Relating molecular models to energy transfer

One could argue that the confusion of the concepts temperature and energy is only a problem of semantics, and therefore does not hinder students' understanding of the role played by energy in chemical reactions. Further study has convinced us that this is not the case. The following question was given to the students:

"Iodine is a molecular substance which sublimates (changes form a solid to a gas) at room temperature. A closed test tube containing iodine crystals is immersed in an isolated vessel containing water at 40 °C.

I. Describe the expected changes.

II. Explain, using the atomic-molecular model, the changes described."

A sample of answers to this question shows that although students have studied about chemical energy for about 9-10 weeks, they still do not understand the relationship between chemical changes and energy changes.

- Iodine is composed of diatomic molecules. After heat is added it decomposes into atoms but an additional amount of heat causes it to regain its diatomic state but in the gaseous state.
- The iodine was in the solid state, the molecular bonds were decomposed and as a result energy was released in the form of heat which heated the surroundings.
- The explanation is that the iodine absorbs energy which breaks the bonds between the atoms and later absorbs more energy in order to form I_2 gaseous molecules from the separated atoms.

4. A TEACHING UNIT DESIGNED TO HELP OVERCOME STUDENTS' DIFFICULTIES

The development of the teaching unit

The results of our studies showed that students do not have a molecular model by which energy changes and temperature changes can be explained. As a result they lack the understanding of energy changes during chemical reactions. It was therefore decided to start the unit with a model explaining the equilibration of temperature by the transfer of energy from an object with a higher to an object with a lower temperature. This model and others used are variations of models presented by Atkins (1984) in his book "The Second Law".

Figure 2 shows parts of the model used in the book. Two objects, one consisting of 3 particles and 3 units of energy and the second, consisting of 6 particles but having zero energy are brought into contact. Energy can be transferred from an "on" particle to an "off" particle and students count the number of ways in which the system, consisting of the two objects can hold its energy. The conclusion is that more than half of the ways are those in which energy is evenly distributed within the system.

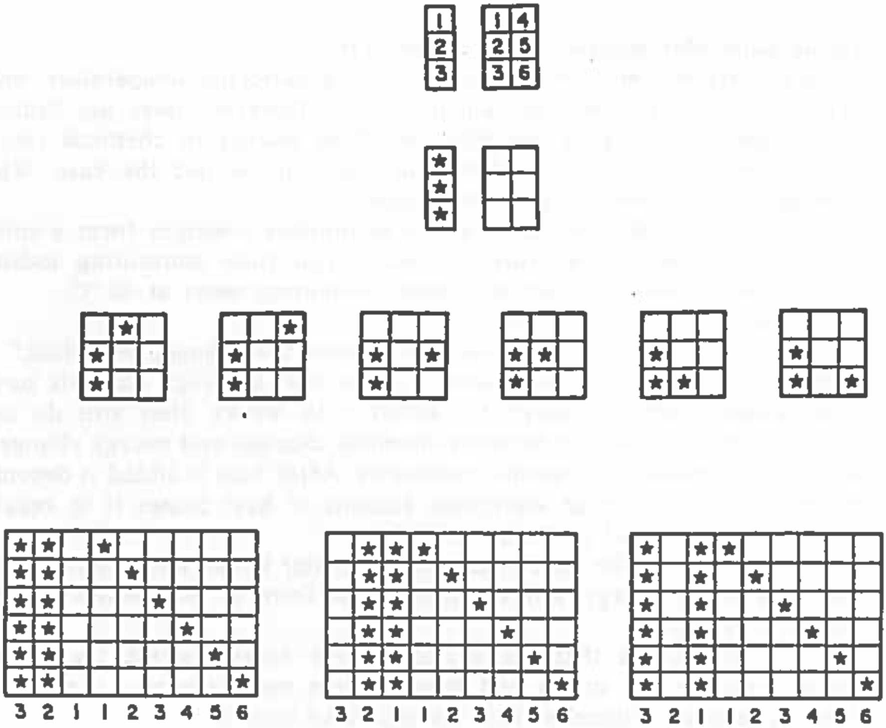

Fig. 2 A model for temperature equilibration.

It was our hope that the students who had studied "Chemistry - a Challenge" for more than a year, were, by now, used to the idea that models are never "completely true". Because of that we felt free to play round with models, being careful to point out the limitations of each of them. For example, figure 3 represents parts of a model used to explain the rise in temperature from an object falling down.

This model is used, later on (fig. 4), as an analogy to bond energies and to the rise in temperature resulting from an exothermic reaction.

A comparative evaluation of the new teaching unit.

Two groups participated in this study. One group (experimental, 7 classes) studied the new teaching unit. The second group (control, 4 classes) studied the unit about chemical energy form a currently used textbook. Both units were similar in the subject matter presented e.g. definitions of heat capacity, enthalpy changes, and various applications of Hess's law etc. The unit studied by the control group was written before we were aware of problems students have with the relationship between the concepts heat energy and temperature. Because of that, not stress is put on models explaining this relationship. Both units, however, use the same graphical representation and appropriate molecular models in order to explain phase changes.

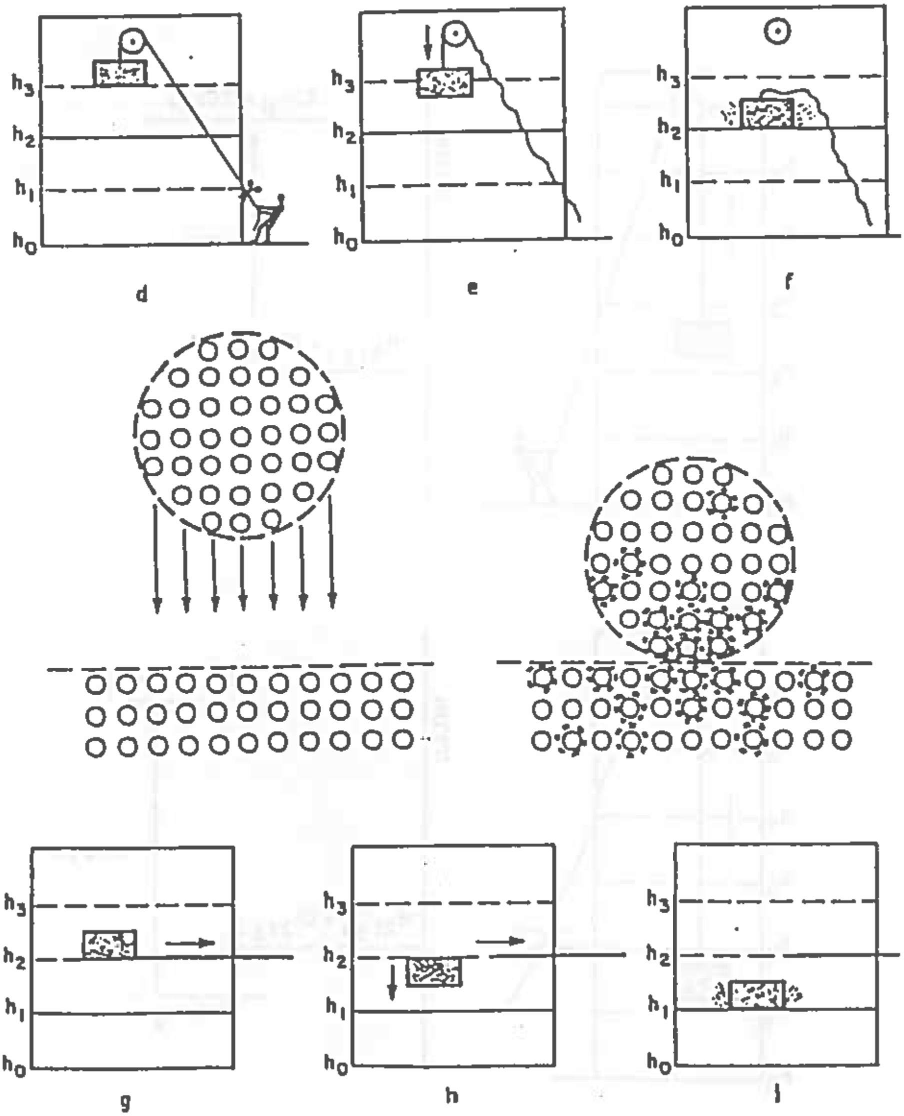

Fig. 3 A model representing the degradation of coherent movement into thermal motion.

All students were given a set of pre and post tests. One of the questions which appeared both before and after studying about chemical energy was one similar to that described in the previous section i.e. dealing with a sample of ice being heated. The analyses of student answers was however different. Each answer was categorized as to whether

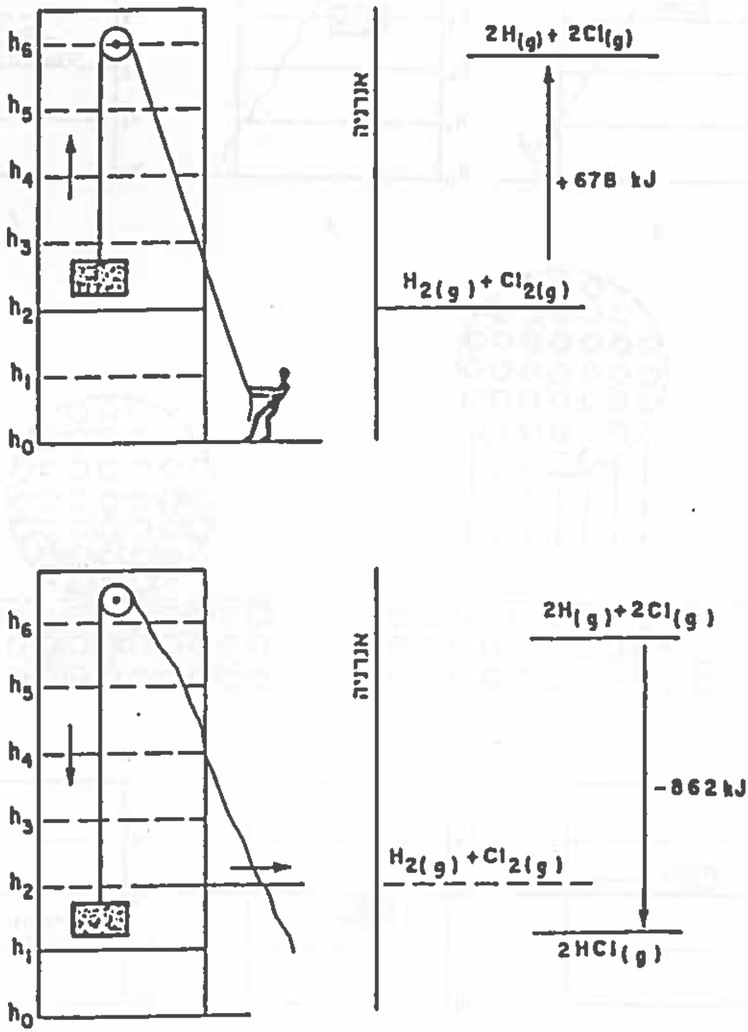

Fig. 4 A model for the energy released in an exothermic reaction.

the student mentioned energy changes, temperature changes and/or model to explain the macro changes. In every category the responses could be either "correct" or "incorrect". In each case the level of students' answers was categorized: i.e. did their answers show links between the concepts.

In the following tables the percentages of students in the two groups, who related temperature change to energy transfer and molecular models to energy transfer, are presented. Only the answers of students who participated both in the pre- and post-tests were analyzed, (Experiment N=103 and control N=57).

Table 3 Relating temperature changes to energy transfer.

	Heating ice correct sentences (%)		Boiling water correct sentences (%)	
	Experiment	Control	Experiment	Control
Pre-test	7	9	6	16
Post-test	43	11	44	2
	incorrect sentences (%)		incorrect sentences (%)	
Pre-test	2	2	5	0
Post-test	2	2	3	9

As can be seen from the results presented in table 3, the percentage of students in the experimental group who related the two concepts rose form 6-7% to 43-44%. The control group showed a different picture - in the context of boiling water, the percentage of correct answers dropped form 16 to 2% while 9% of this group gave incorrect answers at the end of the teaching period.

A similar picture can be seen from the results presented in table 4, showing the percentage of students who related molecular models to energy transfer. Here, again, the performance of the experimental group improved form the pre- to the post-test. One should remember that the results presented in the two tables were obtained by categorizing the answers given by the students. It is quite possible that students who understand the relationship between the various concepts did not "volunteer" this information in writing. In spite of this, it is rather worrying that the percentage of students in the control group who "volunteered" correct relationship, dropped in some of the cases while that of incorrect answers became higher.

Table 4 Relating molecular models to energy transfer.

	Heating ice correct sentences (%) Experiment	Control	Boiling water correct sentences (%) Experiment	Control
Pre-test	4	11	13	12
Post-test	45	14	63	3
	incorrect sentences (%)		incorrect sentences (%)	
Pre-test	7	0	11	3
Post-test	3	11	1	16

5. SUMMARY

The task of helping students to understand the world around them is very difficult. Studies of learning difficulties tend to imply that it is almost impossible to bridge the gap between the scientist's world and the students grasp of it. In the present article we, on purpose, went beyond the scope of learning difficulties and tried to show that if one is careful enough, students' mental picture of the world can be improved.

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CATEGORISING MACRO AND MICRO EXPLANATIONS OF MATERIAL CHANGE

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1. INTRODUCTION

This paper describes aspects of a current piece of research which elicits and analyses explanations of changes in materials. Its aim is to find a way of categorising these explanations in terms of the kinds of actors, transformations and causes used. The first part of the paper describes the current state of this attempt to find an appropriately general, principled descriptive language. In the second part of the paper I will try and show how the framework described earlier is able to make explicit differences in the kinds of explanation used to relate macroscopic phenomena to microscopic particles.

2. WHY CATEGORISE EXPLANATIONS?

This research seeks to outline a framework within which differing understandings of changes in materials (both physical and chemical) can be made explicit. In this approach attention is moved from categorising instances of specific explanations to categorising instances of kinds of explanations. It is, in Andersson's (1990) terms an attempt to formulate a level IV description of explanations. Without such a level of description anyone looking at the mass of evidence existing in the current literature showing that children can give lots of different explanations for virtually any given phenomenon could easily be led to the view that "individuals may construe their environment in an infinite number of ways depending on their imagination" (Pope, 1982).

At a deep level, when one is considering different kinds of ways in which the world can work, I just do not believe this to be true. If teachers are to take account of the different kinds of explanation they meet in their classes, research in this field needs to be directed to articulating some kind of underlying structure to the different explanations we find; to making sense of the diversity of specific explanations in terms of some small number of distinct ways of looking at the world. This work is an uncertain attempt to find a set of elements which can be used to show that order exists in the apparent infinite variety of explanations. In this attempt it draws on ideas from linguistics and cognitive science and is linked to similar work being carried out in other topic areas at the Institute of Education (Ogborn, 1989). In particular, although it starts from a different basis, it relates to ideas raised in the excellent papers by Andersson on causality (Andersson, 1986a) and types of transformation (Andersson, 1984).

3. ELEMENTS OF THE ANALYSIS

Harre (1972) writes of 'formal' concepts such as causation or existence, providing the structure and intellectual foundation of thought. Three linked aspects have been chosen to provide the basis for this exploration of how these formal concepts are employed in explanations of material change. They are:

<u>Aspect</u>	<u>Term given</u>
The entities involved	Role Relationship
The changes that happen	Transformation Type
The causes of the change	Causal Character

These correspond to the three structural units Halliday (1972) saw as forming the ideational function, that concerned with the encoding of experience, in his analysis of the macro-functions of language. These were:

The process itself	Transformation Type
The participants in the process	Role Relationship
The attendant circumstances	Causal Character

Although as will be seen later, these aspects are linked, they will initially be examined in isolation.

4. TRANSFORMATION TYPE

This was developed by thinking about what could be said to change and what stay the same in an explanation of material change. Two fundamental categories were established by interpreting explanations in terms of the perceived continuity of the *existence* or essential *nature* of the entities involved. Additional categories refer to changes where the same objects are seen as always present but in different *arrangements* or forms, or where changes in their *location* lead to different degrees of 'visibility'.

Existence

Here properties belong to objects and if a property disappears then the substance which carries is believed to have disappeared too. The transformation is always one of EXISTENCE as there is not continuity of substance. Words like 'disappear' and 'destroyed' are common in explanations of phenomena such as burning and evaporation e.g. "The atoms ... burn up and then the wad of steel wool doesn't weigh anything any more." (Andersson, 1986b). While Andersson (1986b) rightly cautions against necessarily associating these words with a concept of the non-conservation of substance, some workers have used extended interviews to confirm that this association is often the case. For example Schollum, Osborne and Lambert (1981), commenting on explanations of evaporation of the kind: "It has gone... it has dried up", note that "to many of these children questions such as "where has the water gone to" or "what has the water changed to" were not relevant; the water had not gone anywhere or changed into anything, it had simply ceased to exist".

Nature
In this case the substance is seen to be conserved while one of its essential properties is altered, e.g. Driver (1985) noted that some children believe that things lose weight when they are heated. Although this may be evidence that substance is not being conserved, some of the reported explanations indicate that the same amount of substance is felt to exist after heating, its just that it weighs less. In other words, substance is being conserved but its NATURE is not. Other examples are the cases referred to above where one thing has been seen to change into another - 'stuff' has been conserved but its nature has not. E.g. "The wood, it's changed into cinders..." (Meheut, Saltiel & Tiberghein, 1985), "the steel wool that has burnt turned into carbon..." (Andersson, 1986b). This category is similar to Andersson's (1986) 'Transmutation'. One special type of change of nature is worth highlighting in view of the later discussion of causal agents. This is where what is changed are the entities' property to do something - their POTENCY. As mentioned above, objects are often endowed with properties and changes can be seen as simply the disappearance of this attribute. Two examples of such changes are affecting an acid's capacity to 'burn' by diluting it and the explanation (reported by Séré, 1985) of air getting "tired of pushing and stops pushing".

Arrangement
The essence of this way of thinking is that properties belong to systems rather than objects and changes in properties are a result of the rearrangement of the parts of the system without any creation or destruction of substance. The transformation is one of ARRANGEMENT as there is always continuity of substance. This is the basis for most of the accepted scientific explanations of chemical phenomena but is not confined to them. Examples include: "The oxygen molecule has combined with the iron" (Andersson, 1986b) and "...the atoms of oxygen and hydrogen are rising up from the water (separately) and when they hit something they sort of join together and form little drops of water" (Schollum, Osborne & Lambert, 1981).

Location

In this view there is also continuity of both substance and essence and properties are seen as being carried by objects. Everything that was present at the start is there at the end of the change. Apparent changes are explained in terms of the carrying object of the property being either 'hidden' or 'coming into view'. One widely reported example is the perception of rust being always in existence, either in the air or under the skin of the metal, and coming into view or growing in certain circumstance; e.g. "Its actually under the nail ... the silver coat has worn out and the rust has come out underneath" or "The rust moves from the inside to the outside of the metal" (Schollum, 1982).

Another, more complex, example was reported by Inhelder and Piaget (1958) in their investigation of 'structured wholes'. The experiment involved the mixing of chemicals - acids, bases and indicators - to produce colours. One common explanation of the appearance of a pink colour was "it turned pink, maybe there is paint in the glass". When reading the interview transcripts one striking thing is the lengths to which many children went in an apparent search for continuity of substance. Piaget noted that the colour "may 'go away', 'go down to the bottom', flatten out' to the point where it becomes invisible, or fly away to a beaker more than one metre away" (Inhelder & Piaget, 1958).

This kind of thinking may be an example of the use of a containment metaphor - substances continue to exist but depending on their container they may not show their properties. Lakoff and Johnson (1980) have noted that the use of this metaphor is widespread and they regard it as a base metaphor - see Andersson (1986a) for a discussion of their work in thinking about causation.

Form

Here again, existence and nature are not in doubt. Essentially the same 'stuff' is seen to exist but in a modified form. In some cases the assignment of an explanation to this category is clear. For example, some replies that I have received when asking what happens when ice melts or sugar dissolves often explicitly mention changes in the form of the stuffs involved. e.g. "The bits of water turn from a solid to a liquid form" and "the sugar turns into a liquid form". In other cases the assignment is not so clear but changes that fall in this category (similar to Andersson's (1986) 'Modification') usually involve alterations to colour, size, temperature etc. where the name of the original entity is also given to the product of the change.

Summary of Transformation Types

This section has argued that transformations of materials may be viewed as belonging to one or another of a few distinct categories depending on what is seen to alter and what remain constant during the change. The list used is summarised below together with an exemplar of the form of words which might lead one to place an explanation in the category.

However, these exemplars need to be treated with care since, as was mentioned above, it is essential to note that the terms used in explanations are often ambiguous. The explanation must be seen as a whole, and an initial view of the kind of transformation ascribed may need to be confirmed by further inquiry.

Transformation Type	Exemplar
Arrangement	It joins with... to make
Existence	It disappears
Form	It gets hotter, changes colour
Location	It moves
Nature	It changes into...
Potency	It gets weaker, wears out

5. CAUSAL CHARACTER

One essential distinction in the kinds of causes given in explanations of material change can be made on the basis of where the causal power for the change is seen to reside. Does the reason for the change lie in the nature of the object (or system) being changed or is the change due to the intervention of some outside agent? This distinction gives two of the basic categories of cause used in this analysis - those of agentive and non-agentive changes.

Agentive causes

Within the broad grouping of agentive changes, one can identify a number of distinct types which differ in the roles and character of the agents.

a. Changes can be seen to result from the action of one thing on another.
b. In contrast the actors involved may be seen to be of equal status, acting and reacting on one another.
c. Finally the agent of the change, that within which the causal power resides, may be seen to play no direct part in the change at all, to be a form of indirect agent.

The essence of the first category is that the things involved are not of equal status - one is seen as an active direct agent, the other as a passive, affected object, e.g. the explanation "the rust attacked the metal". In this context it would appear that an important essence of the rust is its causal power, its ability to affect another thing. By contrast the metal is not seen as having such a causal power. In this category of causal character, even when both substances are seen as active the change is often seen as two active/passive acts; e.g. "The water attacks the nail and it forms a rust to protect itself". There is no notion of combinatorial thinking in this category, each actor is seen as having a distinct role and continuity of substance is often seen, as in the explanation of rusting used in the explication of transformation types - "It's actually under the nail.......the silver coat has been worn out and the rust has come out underneath" (Schollum, 1982).

The second agentive category is the essence of most chemists' explanations of change. An example is "The water, air and metal react together to form the rust..". The shift to equality of status is important, because the essence of the change is seen to lie in the INTERACTION of equal partners rather than in the causal power of one participant.

The final way in which an agent can be seen as responsible for a change is as a facilitator. This category is thus called PERMISSIVE; the agent does not directly attack that which is changed, its action is indirect in that its presence is required to allow the change to take place. The prevalence of this type of thinking in explanations of burning was highlighted in a review of the Assessment of Performance Unit's research into children's understanding of chemical concepts: "While the majority of children are familiar with the idea of air or oxygen as a requirement for combustion, it seems that far fewer pupils see the involvement in a specifically chemical way.... Many pupils appear to see oxygen as enabling but not quantitatively participating in 'combustion'. "(Donnely & Welford, 1988).

Similar findings were reported by others, including Meheut who noted that "Although the necessity for oxygen can be perceived, this is not done in terms of its interaction with the combustible" (Meheut, Saltiel & Tiberghein, 1985).

Non-Agentive causes

In another set of causes, the causal power is seen to be not in an external agent but in the substance being changed. These causes seem to be linked to notions similar to the Aristotelian idea of change being a realisation of an essential nature; e.g. a football released above the ground must of necessity fall towards the earth. These types of causes are common, e.g. Nussbaum (1985) writes of children having a concept of substances having a 'natural place' and in their discussion of changes of state, the CLISP (Brook, Briggs & Bell, 1984) refer to children holding the idea of a 'natural state' which substances 'naturally' return to once any constraining conditions are removed. One way of describing the difference between agentive and non-agentive changes is that while in the former a reason for change is felt to be needed, in the latter a reason for non-change is usually given. In Schank's (1982) terms, it could be said that non-agentive changes are satisfied by 'script based explanations.' i.e. those of the sort "that is the way the world is". Only when our expectations fail are further explanations needed.

It is possible to find two sub-categories of this kind of cause. In one, here called ASSOCIATIVE, a substance's latent causal powers are released under given circumstances. Examples from my own work which I would place in this category are "The nail rusts when it gets wet..." and "Ice melts when it gets hot..."

In the other category, the change is seen to result from the release of an external constraint allowing a NATURAL change to take place. An example of this is "The ice melts because you are not keeping in cold any more". At first glance this latter category may be felt to be the same as the PERMISSIVE causes described earlier. This is not so. The crucial difference is that in NATURAL causes, the causal power is seen to res de in that which changes while in PERMISSIVE changes, the causal power lies outside that which is affected - the change would not happen without the active presence of the agent.

Teleology and animism

In addition to the presence or not of external agents of change, explanations may include reference to a system changing in order to realise an external goal, - e.g. "the metal formed the rust to protect itself" - and therefore a category of cause called GOAL DIRECTED has been devised to indicate its presence. It perhaps needs to be stressed that identification of a goal does not of itself imply that the things involved in the change are seen as animate. However, as Séré (1985, 1986) notes, the use of animate metaphor is very common, especially in explanations given by young children. She reports young children talking "as though air has feeling and volition" and them seeing air as "active only if it is disturbed" and (getting) "tired of pushing and stops pushing". Older children also used animate metaphors, speaking of air "trying to..." or "wanting to...." although their commitment to the metaphor was felt to be less strong. The problem is that interpreting this depth of commitment to animate metaphor is not always a trivial task.

Summary of causal characters

The classes of causal character described above are summarised below together with a typical skeletal exemplar.

Causal character	Exemplar
ASSOCIATIVE	It does that when it...
DIRECT ACTION	It hits...
GOAL DIRECTED	It tries to ....
INTERACTIVE	They... together
NATURAL	It does that when you stop...
PERMISSIVE	It lets....

Finally it should remembered once again that in the same way that an individual can use more than one *transformation type* to characterise a phenomenon, he or she may also employ different kinds of *causal characters* depending on the circumstances.

6. ROLE RELATIONSHIP

Taking the view that language must contain clues to the basic categories of thought I began to look at the *roles* played by the various stuffs mentioned in an explanation. Initially I used the Case grammar of Fillmore (1968) later 'filtering' these notions by considerations derived from Halliday's (1985) functional grammar. Case grammar is based on "a set of universal, presumably innate concepts which identify certain types of judgements human beings are capable of making about the events going on around them..... about such matters as who did it, who it happened to and who got changed." (Fillmore, 1968)

Like other workers who have tried to use them (Harris, 1985) I found that when applied to explanations of change, Fillmore's original list of cases were not wholly appropriate. In particular their animate/inanimate distinctions were not the most useful. In addition, the role ascribed to actors in a change is intimately related to the type of cause given for that change (see list below) and in developing these links different cases from Fillmore's original conception were appropriate. The set of cases currently in use and the links between them and the perceived causal characters are shown below.

Case	Role
AFFECTED	The object affected by the change
DIRECT AGENT	The active agent in the change
INDIRECT AGENT	The active permitter of the change
CONDITION	The passive conditions required for the change
CONSTRAINT	The active constraint which when removed allows the change to take place
GOAL	The goal (if any) of the change

Causal character	Case needed
DIRECT ACTION	DIRECT AGENT (DAGENT)
INTERACTIVE	2 X DAGENT
PERMISSIVE	INDIRECT AGENT (IAGENT)
ASSOCIATIVE	CONDITION
NATURAL	CONSTRAINT
GOAL DIRECTED	GOAL

A summary list of exemplars is given below with the entity belonging to the appropriate case highlighted in bold. More examples, together with a further explication of the attributes of the various cases can be found in appropriate sections of the discussion of causal character.

Case	Example
AFFECTED	The nail is attacked by the water
DAGENT	The nail is attacked by the water
IAGENT	The air allows the candle to burn
CONDITION	Ice melts when it is hot
CONSTRAINT	Ice melts when you move it away from the cold
GOAL	The nail tries to form a coating...

7. REPRESENTING THE ELEMENTS

Combining the second and third elements of the analysis as outlined above gives a number of basic schemes, not too dissimilar from the early ideas of Schank (Schank & Ableson 1972), which explanations might be found to fit, e.g.:
ACTIVE AGENT ACTS ON PASSIVE OBJECT - The water attacks the nail
ACTIVE OBJECT ACTS ALONE - Ice melts when you don't stop it
EVENTS HAPPEN IN GIVEN CIRCUMSTANCES - Ice melts when it gets hot

Each of these may lead to a number of the kinds of transformation described earlier. Since the whole point of the form of analysis used is to show that there are only a limited number of possible kinds of explanation and that these are constructed by combining, in restricted ways, the elements described earlier, a systemic network (Bliss, Monk & Ogborn, 1983) seemed an appropriate representative tool. A simplified version of the network currently in use is shown below. It contains two extra elements in addition to those described above. One indicates whether a change is labelled or described, the point being that labelling a change - just giving it a name - may be a way of avoiding explanation by 'explaining away' (Schank, 1986). The second element is employed where microscopic entities are used in the explanation and illustrates the perceived link between the micro and macro levels. This network has been used to re-interpret explanations of change found in other research reports as well as empirical data I have collected, to see whether collections of such results can be given a more unified description. As a result, I now think it provides a reasonable basis for examining understandings of change, although as yet I can say nothing about whether there is any developmental pattern to the kinds of explanation it depicts.

8. A NOTE ON EMPIRICAL WORK

A lot more empirical work needs to be done before any firm conclusions about patterns of explanations can be drawn. The empirical work conducted so far has been designed to aid the development of the network as an analytic tool. Those interviewed have ranged from 6 year old children in infant classes to (non-science) B.Ed. and (science) PGCE students. The tasks and prompts used have also varied - from questionnaire type responses to written or pictorial prompts to (tape recorded) discussions of one or more of the phenomena. The point of this was to try and elicit as wide a range of explanations as possible, the better to test the network. The network has been further tested by applying it (as in the examples above) to examples culled from the literature of explanations given to other researchers.

It was repeatedly mentioned earlier that any one individual can explain a given phenomenon in a number of different ways depending on the

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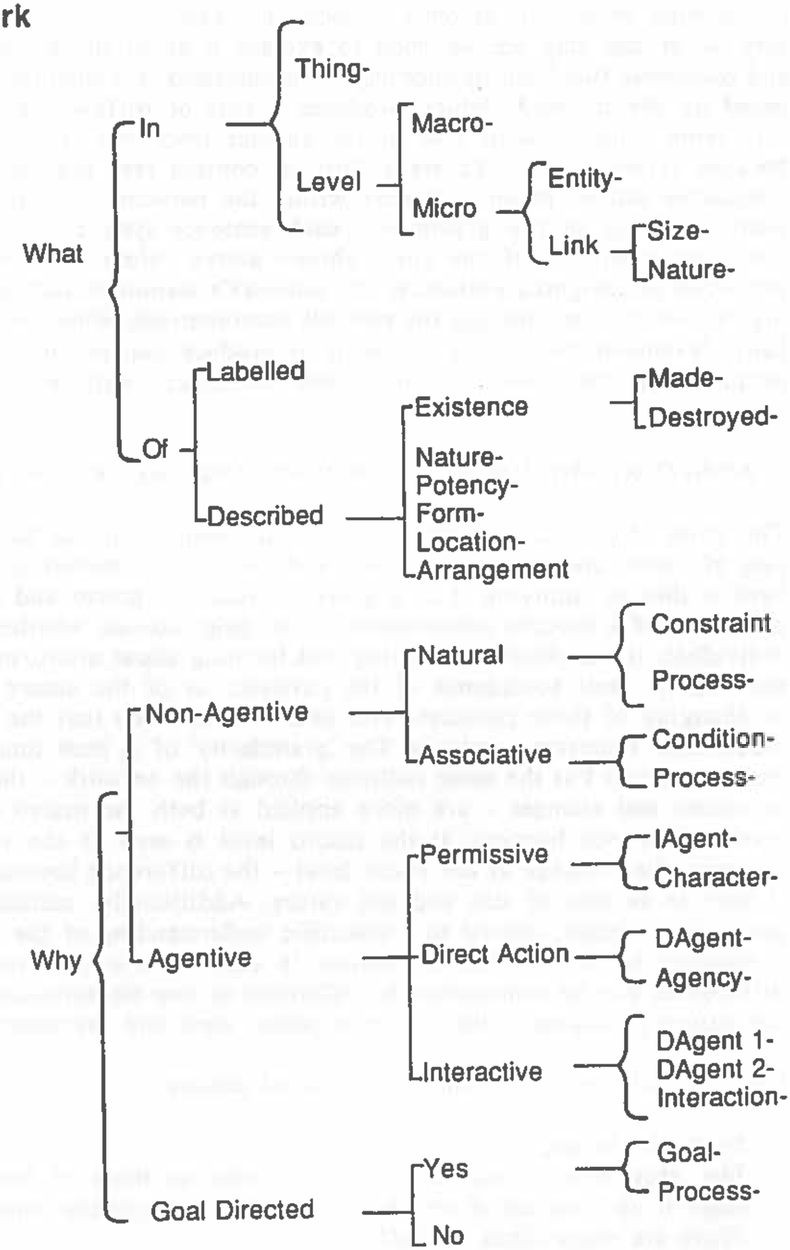
Network



What
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Form-
Location-
Arrangement
Why
Non-Agentive
Natural
Constraint
Process-
Associative
Condition-
Process-
Agentive
Permissive
IAgent-
Character-
Direct Action
DAgent-
Agency-
Interactive
DAgent 1-
DAgent 2-
Interaction-
Goal Directed
Yes
Goal-
Process-
No

audience. The data collection techniques I have used so far are not ideal for homing in on this as once someone has explained something in one way he or she may see no need to explain it again in another. To try and overcome this I am developing a computerised 'explanation generator' based on the network, which produces a host of different explanations (differing both in kind and in the entities involved). This is possible because systemic networks are a form of content free grammar and the alternative sets of possible choices within the network correspond to the sentence types in the grammar - each sentence type corresponding to 'shell explanations' of the form shown above. 'Real' explanations are produced by assigning entities to the network's terminals and then choosing randomly from amongst the possible combinations. When this system is fully developed the idea is to use it to produce explanations which the people being interviewed can then accept or reject - with reasons.

9. APPLYING THE IDEAS TO UNDERSTANDING OF PARTICLES

This form of analysis is designed to provide insight into the basic categories of cause and change used in explanations. Of particular relevance here is that by applying it to a given individual's macro and micro explanations of a specific phenomenon it can help indicate whether, for that individual, the problem in teaching and learning about micro/macro relationships is their acceptance of the *existence* or of the *nature* and *ways of changing* of those particles. The results seem to be that the latter is a much more important problem. The 'granularity' of at least some stuffs is easily accepted but the same pathway through the network - the same set of causes and changes - are often applied at both the macro and micro levels. Whatever happens at the macro level is seen as the result of a corresponding change at the micro level - the difference between the two is seen to be one of size and not nature. Additionally, certain kinds of causes and change, central to a scientific understanding of the world, are noticeable by their relative absence in children's explanations. These differences can be summarised by reference to two stereotypical views of the nature of change - the 'common-sense' view and the scientific view.

Characteristics of a common-sense view of change.

Properties belong to *objects*.
The properties of an object *are the same as* those of the bits that make it up - not all of which may be visible at any one time.
There are *many* kinds of stuff.
Changes in macroscopic properties are the result of *equivalent changes* in the microscopic particles.
If properties change it is because the *bits that cause that property* have moved away, come into view, changed form, grown or disappeared. New properties can be caused by the arrival of new bits.

Characteristics of a scientific view of change.

Properties belong to *systems*.
The properties of an object are *different in kind* from those of the bits that make it up.
There are fundamentally only a *few* kinds of stuff.
Changes in macroscopic properties are the result of changes in *arrangements* of *unchanging* microscopic particles.
If properties appear or disappear it is because the arrangement of an *unchanging set of continuing* particles has altered - at a fundamental level substance is always conserved.

This is meant to illustrate that the whole relationship between parts and wholes is different in the two views. Science has a very specific view of this relationship which is of much wider applicability than material change. In science bits interact to produce wholes with different properties from the bits. This interactive view of change and properties is as true of say dynamics as it is of chemical change. In chemistry things are further complicated because matter is viewed as existing at several different levels of organisation. Differences in the natures of objects at one level can be explained by reference to differences in arrangement of a common set of sub-particles at a more micro level. In this way a few elemental kinds of stuff at one level can produce a much more diverse set of stuffs at a higher level and differences between the natures of these elemental stuffs are explained by reference to different arrangements of a (smaller number) of elemental stuffs at a lower level.

In explaining the difference between:	The unchanging bits are:
Liquid water and ice	Molecules of H_2O
H_2O and H_2O_2	Atoms of H and O
Atoms of H and O	Protons, neutrons, electrons

In contrast, the 'common-sense' stereotype contains no combinatorial thinking, simply a 1-1 relationship between properties, causal powers and entities at the two levels.

Outlining a problem in this way does not of course solve it. However, if the ideas outlined above are felt to have some validity (not necessarily be correct!) then they may be of use in helping towards a better description and categorisation of the problem in that they point to a general way of thinking removed from the specifics of any one change. They suggest than it may be fruitful to search out and develop analogies, tools and experiences which, at a child sized level, illustrate the ways of thinking required for a full scientific understanding of the micro/macro relationship. Such activities may point to a developmental pathway which avoids children having to cope with abrupt changes in scale and kind of explanation (the latter usually implicit) at the same time.

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JUMPING TO THE ATOMS: THE INTRODUCTION OF ATOMS VIA NESTING SYSTEMS

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1. ANOTHER REFERENCE FRAME OF TEACHING

Ten Voorde (1990) identified in his plenary lecture 'On teaching and learning about atoms and molecules from a Van Hiele point of view' three frames of reference A, B and C relating to the philosophy of science teaching. My frame of reference is frame D: rather than taking phenomena or the school science experiments first and then trying to generalize and explain, I prefer (in topics like atoms or particles) to begin with text, or sayings, or just concentrate on a single concept. I might begin with the question: Do we - pupils and teacher - understand, what is written in this book, in this article, do we understand, what someone means, when he or she says this?

So neither the science-content takes first priority, nor how children would explain, what they see, feel, smell and so on, but rather texts and statements we find in books etc, and the way of thinking and arguing, which lies behind it. Of course, phenomena and experiments have an important place in my teaching, but they are not the starting point. They cannot be omitted, though, as we do have to experience first hand (if possible) what we ware talking about, - experience in a double sense: perceptive and manipulative experience as well as experience of thought and reasoning.

By proceeding in this way, I don't have the problem, that many other science educators have. For instance I never have to give an explanation. We find it, there, in the book, and then we discuss how convincing this explanation is. And if it does not convince a pupil, it is not necessarily he or she, who is at fault or weak. It might as well be the author. So it is never mine, the teacher's explication or model, which might not be consistent. (Viennot & Rozier, 1990)

It is a kind of continious training of judgement. And I think it is an important goal in order to educate children to be aware and self-confident adults. It is my way of trying to contribute to 'scientific literacy'. I call my approach to teaching 'Verstehen lehren' - teaching how to understand - understand people in the first place, people, who are talking about observations or ideas in the field of chemistry and physics.
'Verstehen lehren' is a formula coined by Martin Wagenschein (1982). Wagenschein has given me great inspiration. But Wagenschein would rather begin with a consciously selected phenomenon, than with a text.

On our subject he says for instance: 'Brownian movement - this approach seems to be reasonable in the direction of Democritus' atomism. If combined with other (chemical) conclusions, it can lead - *later on* - to the image of ideally elastic balls, which push each other without touching, and indeed - literally - make up a perpetuum mobile, (providing we are not including heat). And as the molecules themselves cannot be warm or cold, they are no longer 'real' portions of water'. (1989, p. 55).

Wagenschein's intention of 'Verstehen lehren' was to understand the laws that govern the realms of nature or of mathematics. I shifted the accent: to understand, what people say about the natural and mathematical phenomena, seemed to me to be equally important. And by trying to do this one cannot avoid forming one's own opinion about the phenomena considered. Thus we can never bypass the phenomena.

2. TEACHING EXPERIENCE

What I want to claim in this article is an introduction to atoms and elementary particles. I have taught it several times in grade 8 of the Hauptschule, grade 9 of the Realschule, and it is a standard topic in my teaching of chemistry to students, who will become chemistry teachers. The justification for teaching this topic is different for different groups. The fact, that atoms cannot be omitted and should not be omitted in the Hauptschule is politically motivated. To leave the topic of nuclear energy out of the curriculum, would be taken as an attempt to keep the working class away from the fundamental political issue of nuclear power. A discussion about it cannot begin without the word 'atom'.

Now, if I have the task of teaching atoms, let us say to Hauptschule-pupils, I assume, that they have already heard - but don't know much about them. I see my task as giving them an idea of what a strange world the world of atoms is, rather than oversimplifying matters - or deceiving the children, if you like - by doing as if atoms were objects like tables or billard-balls. And if the pupils encounter difficulties in understanding, I openly admit to them, that scientists have met the same difficulties. And I am not worried, if some questions are left open - on the contrary: they give me hope, that the pupil will stay interested and retain an inquiring mind.

3. THE VIEW TAKEN ON ATOMS

Werner Heisenberg (1942) says: 'The elementary particle fundamentally is not a material entity in space and time, but only a symbol, so to speak, by the use of which the laws of nature appear in a particularly simple form'. And a few sentences further on he says: 'In order to give a clearer notion of what is meant by symbolic nature with regard to the modern concept of the atom, we can say: the question asked in modern physics, whether and how an atom exists is somewhat similar to the question asked in mathematics, whether the square root of the negative number exists. Although we are taught that it does not exist among the ordinary numbers, important mathematical laws appear in their simplest form only if the square root of the negative number is introduced as a new symbol. And to this extent its very existence is founded upon these laws'.

Heisenberg is obviously referring to the impossibility of having visual images of the proton, electron, photon, atom and so on. He refers to their radical unimaginability in a visual and tactile sense. So vividly illustrative texts and illustrations, which are very common not only in Germany, but all over the world, for instance drawings, where sugar is seen as consisting of little sweet globules, or where the formation of a solution is taken as the process of repeated grinding of sugar cubes, which are then mixed with the ultimately tiny waterdrops, or where a chemical reaction, for example the reaction of sulfur with iron, is pictured as a mere reorganisation of small yellow and grey balls, - all basically misunderstand in the light of Heisenberg's statement the nature of atoms and elementary particles. In my opinion they are misleading and harmful. I (1989) do discuss this with the pupils.

So I am talking of the unimaginable atom, not of particles as models of understanding. The unimaginable atom however is clearly thinkable. It's evidence cannot stem from the analogy of litte billiard balls, but rather from the experience of thinking. Therefore we do a lot of comparing and reasoning.

4. CONCEPT DEVELOPMENT

Having the abstract concept of atom in mind, it seemed obvious to consult Piaget's writings on formal operative thinking. Piaget (1973) identified three roads to atomism. Two of them he called analogies, the third one a reconciliation. He named the first one 'the metaphysics of dust': a sunbeam in a dark and dusty room produces a magic world of tiny particles moving about, and a heap of sand or a desert hints at a world being made up of particles.

The second one is the analogy of geometry and algebra. Just as every number can be regarded as being composed of the unit 1, 3 being 1 + 1 + 1, 5 being 1 + 1 + 1 + 1 + 1, or just as a line can be regarded as being made up of an infinite number of points, or an area being made up of an infinite number of lines and so on, likewise matter can be regarded as being made up of particles. I think it amounts to more than an analogy, however, it is atomistic thinking in essence. Unlike Piaget I would not call it an analogy, but rather a mode of comprehending; in German: ein Zugriffsmodus (Buck, 1984/85). But the name, and the theory behind it, is not relevant here.

Then thirdly, Piaget (1974) says: in order to reconcile qualitative change, transformation, with quantitative invariance, people invent the concept of atoms. 'To invent' is Piaget's word. For instance: when dissolving a lump of sugar in water one observes a qualitative change: the lump disappears, is liquified. However, as nothing escapes from the cup, nor enters it, quantitative invariance of the substances water and sugar is postulated or taken for granted. Invariance means that nothing changes, disappearance does imply a change; how can this contradiction be overcome? If one says, the sugar molecules as well as the water molecules move about, but taken by themselves stay unchanged, the contradiction no longer exists.

And indeed, this was the situation in philosophy, when Democritus lived: he gave to the process and the unescapable transformation the status of basic essence: "You never enter a river twice". Whereas Parmenides only accepted the one and only spheric whole. How could these opposite philosophies be united, be reconciled? Democritus' solution was intriguingly simple: instead of Parmenides' one all-including whole he took the many units, and reduced transformation to translocation (see also (Buck, 1979).

Piaget quotes a number of testees, who spontaneously develop the concept of atoms, for instance when he let sugar dissolve in water or corn pop up to popcorn. And if a testee did not come up with atomism, Piaget simply did not consider him or her sufficiently advanced in his or her development.

This is however a rather simplistic view and not quite useful to the teaching of chemistry and physics. Obviously pupils don't take the tension drawn up between transformation and invariance as suspense. And as a matter of fact, chemists for instance by creating and using the concepts of 'substance' or of 'chemical element' (Buck & Lenz, 1989), the physicists by designing the concept of 'energy' (Buck, 1984) do reconcile transformation and invariance without any urgent need to fall back on atoms. To many children it is not at all contradictory to say, that on burning magnesium, the magnesium is changed and at the same time preserved in the magnesia.

Now, as Piaget's first psychogenetic road to atomism, the analogy to dust or sand, does not deal satisfactorily with the real situation: a sulfur atom is not a tiny yellow particle, and as the second road - the atomistic mode of comprehension - is not everybody's approach, and as the third road via the contradiction between transformation and invariance is rather philosophic and not necessarily leading to atoms, I looked for another road to atomism. It is probably not a psychogenetic road, but rather a didactic one.

Although I am not sure, if a sequence of prerequisite concepts must have been developed beforehand, I expect it to be helpful, if the following concepts have been discussed and to some extent made clear to the pupils:

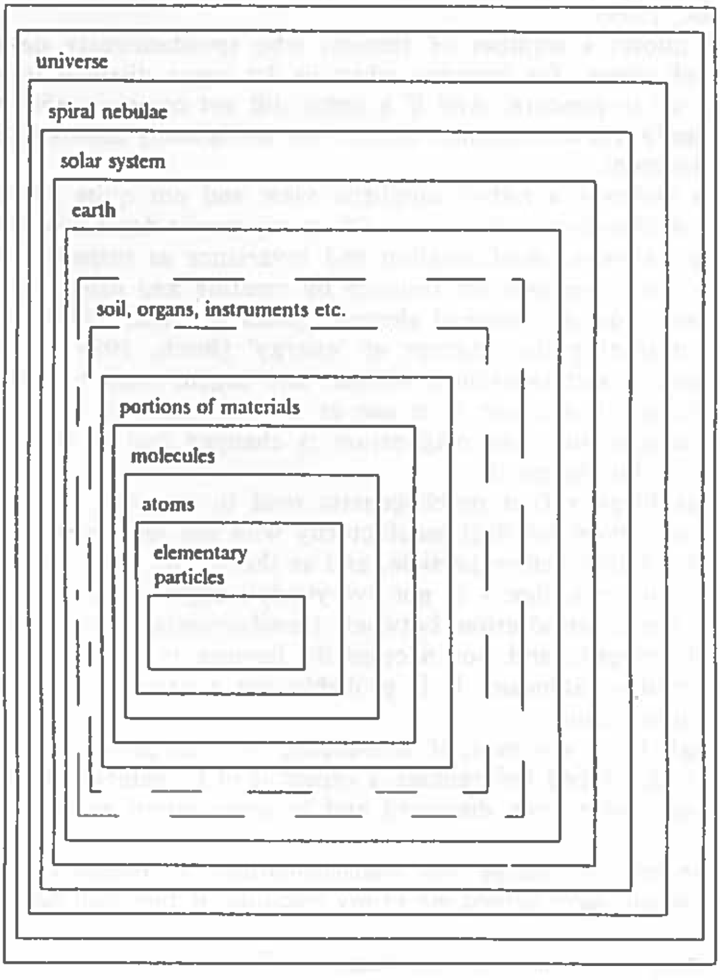
- the concept of change and transformation (T. Brosnan's categories (1990) would have helped me in my teaching, if they had been available then);
- the concept of invariance (see Piaget (1973);

- the concept of substance in the sense, that it is discussed and understood, why we for instance may call ice, water and steam a single substance, and what the properties of this substance are.

When talking about these three concepts, I tried to make the pupils aware, that we can also be sure about 'things', we cannot point at, for instance number, evidence, etc.

5. THE RATIONALE

'System/component' was also a concept we worked at extensively. The children liked to find examples themselves - knives and racing cars from the boys, trees and handbags from the girls - and name the properties their systems would have, but it's components would not have and vice versa.



When it came to the topic of atoms, all objects and experimental arrangements we had been working with and talking about during the last six weeks were exhibited in the classroom. The problem was introduced via a set of slides. I reasoned the following way: take a galaxy, for instance the one seen in what we call the milky way. It is obviously a system; our solar system is part of it. Our solar system, the sun together with the planets, the earth being one element of this system, is a system within this system. The earth again is a system of components, say oceans and continents; the continents are a system of mountains, rivers, cities and so on; the cities are systems of streets, houses, etc., the houses systems of halls and rooms, the lecture room is a system to which we, too, belong as its components; we ourselves are systems of arms, legs, trunk, head and so on; our head is a system of the components nose, eyes, hair etc.; the hair again is a system, which can be studied and be seen under the microscope as being composed of components. (I might as well have used the fabric of my sweater, like in R. Millar's (1990) slides from Salter's science. Pupils can observe this quite well under the microscope.

This sequence may lead us to the question: are these hairfibres also systems of still smaller components? Unfortunately at this point the microscopes let us down. A hairfibre cannot be pictured sharply. So, what is going on? What can we expect?

It is clear: if you go on asking: what are the components of the system 'hairfibre' you come to the tertiary protein structure, this protein structure is a system again, a system of aminoacids, and the aminoacids are systems of atoms, so via the elementary particles you end up with quarks. Clearly this nesting system as shown on the preceding page depicts the material world.

However, this is only part of the approach. In playing this systems-and-components-game one thing should be made explicitely clear: the qualities of a given component are usually not the qualities of the system, it makes part of and vice versa. A sheet of zinc cannot produce electricity by itself, but together with, say, graphite, mangane, ammonium chloride and a few more ingredients, in other words: contributing to the system 'battery', the system battery has the quality of producing an electric current. This quality is obviously a property of the system, not a property of any one of its components. One can eat with one's mouth, but with a tooth alone one cannot eat. I should give you many more examples, beautiful examples contributed by the children.

What I have just explained can be summarized in the diagram shown above, or if you prefer, through the picture of a Russian doll set: one doll after the other nested into the next larger doll. Going inward and outward, nesting and setting apart, is the very heart of my way of introducing atoms. It depends on the explicit reference to change of properties, when passing from the system to the component and vice versa.

I will not conceal that there is a threshold in it, that one has to cross quite consciously. That is why I gave my contribution the title, 'Jumping to the Atoms': how do I get from the hairfibre, the last station, which can be observed visually - under the microscope - to the protein-structures, of which we only get patterns, like a rabbit's trail. When one sees its trail in the snow, nobody would dare to say, that you see a rabbit. The jump lies in the fact, that we must not expect ever to catch the sight of the rabbit. As Heisenberg says, the atom is only a symbol, ...

In other words: when teaching about atoms consistently, we cannot teach science-content without epistemologic content. I have tried different ways to perform this jump: by talking for instance about the jump to the invisible itself, or by starting from both sides: from the universe as well as from the elementary particles (see the diagram above), building up the nestings from outside as well as from inside. In any case, this threshold, this jump is always to be discussed with the pupils. These discussions are essential, as evidence of atoms and their structure is gained from thinking and reasoning, not from pointing at little spheric objects.

My method of teaching atoms is probably 'ostensive teaching', as R. Millar (1990) calls it. My method of introducing atoms is more extensively described in Buck (1981, 1984).

6. PUPILS' REMARKS AND A POSTSCRIPT

On one occasion when we were discussing the diagram of nesting systems as explained in the preceeding chapter, Andreas without being asked remarked excitedly: 'At the universe it ends! Because since you are within the system of systems you can never look at it from outside'. And indeed, this is quite a sophisticated, abstract idea. Such a statement would not be possible without an understanding of the rationale. Even if there were a second (or more) universe(s) outside and juxtaposed beside ours, we could sum up both (or all) to a superuniverse.

Later, when we looked at the well-known ball-and-orbit-pictures of atoms in our schoolbooks, Sonja (equally excited) objected: 'But if you cannot see atoms, you cannot make pictures of them!' Sonja is right. She is beginning to understand that it is our imagination, and not observation which guides us.

Andreas and Sonja were so excited that their contributions could not be ignored by the teacher. When looking at the old videos of my first teaching attempts, I find more and more instances where I cut off the only hesitatingly produced thoughts and arguments of the pupils. It needs some sensitivity training in order to conduct a discussion in the spirit of 'Verstehen Lehren'. In 1979, when I began to teach in the way described, I still stuck too closely to the reference frame of knowledge-transfer. My aims have developed more and more towards the attainment of insight within the pupils. This can be done only by the pupils themselves. Here I come close to the constructivist idea of teaching and learning. What keeps me outside the constructivist fence is the metaphor used. Wat goes on in the young minds of our pupils - as I see it - is organic growth and differentiation of concepts rather than a construction of their personal houses of science with home-made (or prefabricated?) concept-bricks.

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ON RELATING MACROSCOPIC PHENOMENA TO MICROSCOPIC PARTICLES AT THE JUNIOR HIGH SCHOOL LEVEL

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1. INTRODUCTION

Several studies (Driver et al., 1982; Brook et al., 1984; Driver, 1985; Nussbaum, 1985; Gonzalez, Blanco & Martinez, 1989) have shown that the majority of junior high school students use alternative particle ideas to explain everyday phenomena while other students do not make any reference to particles when interpreting situations which could be explained by the particulate theory of matter. Some studies have also shown (Brook et al., 1983; Osborne & Freyberg, 1985; Sequeira & Leite, 1988a) that some students have difficulties in understanding the particle model. Despite their acceptance of the existence of particles, they believe that the empty space between particles is filled up with other particles (often, they say, with air), that is, they do not accept the existence of vacuum between particles in a given substance. In a similar study about secondary students' alternative conceptions (Cachapuz & Ribeiro, 1986) it was found that most of 6th, 8th and 10th graders seldom used the concepts of atom, molecule or particle to define the concept of gas. Also, in a recent study by Ure and Colinvaux (1989) it was found that adult students in an evening school gave explanations for the vaporization and condensation of water which showed that they thought "water can turn into air and air into water; or that air and water in the form of air are the same thing". Another study (Sequeira & Leite, 1988b) gave some indication that students have some difficulty in defining atom which leads them to misuse the particulate theory of matter.

As Mas, Perez and Harris (1987) have argued, "the existence and persistence of adolescents' preconceptions about the material nature of gases is an important factor to be considered in the teaching of principals of conservation of substance, mass, and weight".

The same could be said in relation to students' alternative conceptions about the structure of solids and liquids.

The objectives of this research are to investigate whether or not junior high school students use the particulate theory of matter to explain everyday situations, to identify the ideas about particles used by the students in their microscopic explanations and to gain some insight on the reasoning done by the students when they explain macroscopic phenomena which could be interpreted by the particulate theory of matter.

2. METHODOLOGY

A sample of 182 students was used as follows: two classes of 8th grade regular students, two classes of 8th graders from an evening school (adult students) and three classes of 9th grade regular students. All these students were from secondary schools of the district of Braga.

At the 5th grade all the students had been taught that matter is made up of particles which are moving with empty space among them. They were also taught that spacing between particles is larger for the gaseous state than for the liquid state and for this one is larger than for the solid state, increasing with temperature, in any case. Also, they had already studied that the fundamental particle of matter is the atom, without any reference to its structure. In the 8th grade the students learn about the structure of the atom and molecules, chemical reactions and physical transformations. However, eighth graders were never taught chemistry and ninth graders had a semester of chemistry in the previous year.

A questionnaire was organized by the authors, based on problems used in a previous study (Driver et al., 1982). Basically, the questionnaire has six problems (Appendix 1) dealing with everyday situations which involve physical phenomena (e.g. dilation, dissolution) that can be explained by the particulate theory of matter, although this theory is never mentioned, nor is any particle related concept (e.g. If you put a spoon of salt in a glass filled up with water, a bit later, all the water will taste salty. Explain why this happens.). At the end of the questionnaire, the students were asked: "In your opinion, what is an atom?". This question intended to find out if the students who hold an acceptable concept of atom (at least that the atom is the fundamental particle of matter) could use the corpuscular model to explain macroscopic phenomena.

The questionnaire was administered by science teachers of each class at the beginning of the academic year and the students were asked to answer to it individually and in writing.

In order to clarify some of the students' answers to the questionnaire, a group of nine students was interviewed. This interview did not include any additional problem but rather aimed to ascertain the students' reasoning behind their answers to the questionnaire.

The students' answers to the first six questions of the questionnaire were classified in eight categories as follows:

- *correct microscopic* (e.g. The particles of salt spread through the water and occupied the empty spaces among the particles of water);
- *correct macroscopic* (e.g. The salt spread and it mixed together with the water but remains salt);
- *descriptive* (naming the phenomena without explaining them, e.g. The salt dissolved);
- *empty spaces in matter* (without reference to particles) (e.g. The salt penetrated into the empty spaces of water);

- *use of alternative particle ideas* (e.g. The particles of salt penetrated into the particles of water; the particles of salt dissolved);
- *incorrect (alternative) macroscopic* (e.g. The salt disappeared and no longer exists as such);
- *unclassified* (irrelevant, incomprehensible responses);
- *no answer or don't know.*

The students' answers to the question "What is an atom?" were classified taking into account the main characteristics invoked by the students, such as: size, shape, structure, electric charge, emphasis on the atom as a constituent of matter, atom as a particle, atom as molecule and others.

The data were analized by school year and displayed in contingency tables. The significance of the relationships was tested by the chi-square test.

3. DISCUSSION OF RESULTS

The results of this study are presented and interpreted taking into account its main objectives:

a. to investigate whether or not students spontaneously use the particulate theory of matter to explain everyday situations,
b. to investigate the students' reasoning about the topic and
c. to investigate students' knowledge about the atom.

a. Spontaneous use of the particulate theory of matter

Table 1 shows the percentages of students who explicitely used particle related concepts (particle, atom, molecule, ion and corpuscule) to explain everyday problematic situations presented to them, either correctly or incorrectly. We can see that the adult students (8th graders without instruction in chemistry) were the ones who used less particle related concepts even when compared with regular 8th graders (who also did not receive instruction on chemistry). Ninth graders (who received instruction

Table 1 Percentage of students explicitly using particle related concepts.

						(N=182)
	8 th grade				9th grade	
Problem	Regular st. (n= 58)		Adult st. (n=40)		Regular st.(n=84)	
	f	%	f	%	f	%
Ball	1	(2)	1	(3)	8	(10)
Car tyre	0	(0)	0	(0)	4	(5)
Ice	0	(0)	0	(0)	4	(5)
Sugar	9	(16)	3	(8)	19	(33)
Salt	10	(17)	4	(10)	28	(33)
Water	0	(0)	1	(3)	3	(4)

Note: Particle related concepts: particle, atom, molecule, ion, corpuscule.

in chemistry, namely the structure of atoms and molecules) were the ones who used more particle related concepts, as expected, although the percentages were still low (from 4% to 33%). Table 1 also shows that the highest percentages for the three groups of students were obtained on the "sugar" and "salt" problems. This may be explained by the fact that these two problems are studied in school and are included in the text-books (5th grade Natural Sciences and 8th grade Chemistry). When we interviewed some students about the questionnaire, we asked why they did not use the corpuscular model to answer to the problems of the questionnaire, and we found out that most of them did not feel the need to do so.

b. *Students' explanations of macroscopic phenomena*

Table 2 shows the students' performance on explaining the everyday situations contained in the questionnaire. Although all the situations should be interpreted by the students through the particulate theory of matter, a global analysis of table 2 enables us to conclude that almost all students either are unable to use correctly or do not feel the need to use the particulate model to explain the situations given to them. In fact the percentage of correct microscopic answers is higher than 10% only in the case of 8th grade regular students when answering to the "salt" problem (14%) and 9th graders when answering to the "salt" problem (27%) and the "sugar" problem (15%).

Table 2 Students' performance on explaining everyday situations (%) (N=182).

Category of answer	Ball			Car tyre			Ice			Sugar			Salt			Water		
	8 r	8 a	9 r	8 r	8 a	9 r	8 r	8 a	9 r	8 r	8 a	9 r	8 r	8 a	9 r	8 r	8 a	9 r
CORRECT MICROSCOPIC	0	3	2	0	0	1	0	0	5	9	0	15	14	8	27	0	3	4
CORRECT MACROSCOPIC	2	0	20	3	3	14	0	0	0	28	30	25	29	35	31	40	40	52
DESCRIPTIVE	2	10	6	33	48	32	12	10	4	41	48	36	19	25	15	48	30	39
EMPTY SPACE	0	0	0	0	0	0	0	0	0	3	3	12	3	0	11	0	0	0
ALTERNATIVE PARTICLE	2	0	7	0	0	4	0	0	0	3	8	7	5	3	5	0	0	0
ALTERNATIVE MACROSCOPIC	64	50	37	28	28	21	62	50	60	7	0	1	2	0	1	0	3	1
UNCLASSIFIED	19	38	23	29	23	23	19	33	30	9	13	4	22	28	8	7	23	4
DON'T KNOW	12	0	5	7	0	5	7	8	2	0	0	0	5	3	1	5	3	0

Note: 8 r = 8th grade regular student (n=58); 8 a = 8th grade adult student (40); 9 r = 9th grade regular student (n=84).

Although the percentages of correct macroscopic answers are in some cases very low and never are higher than 52% ("water" problem, 9th grade) they tend to be higher than in the case of correct microscopic answers. A possible explanation for students' higher performance on macroscopic answers might have been revealed by the interview as some of the interviewees were not willing to use the particulate model (even when they were asked to do so) based on the argument that the particle based explanation would "make things more complicated" (9th grader, 14 years old). The interviewees who were forced to use the particulate model were, in most cases, unable to use it correctly and when they were asked to draw some water (after being told that it is made up of particles) they either stated that they could not do it because particles "are so small that no one can see them" (9th grader, 14 years old) or they drew a continuous picture of the water. This may indicate that students have some difficulty in accepting the particulate model even when they are made aware of it.

A relatively large percentage of students gave descriptive answers, that is, they identified the physical phenomenon involved in the problem but they did not give any further explanation of the situation. It may be that for these students the name of the phenomenon is all what is needed to answer to the question as Ure and Colinvaux (1989) concluded in a study about vaporization and condensation of water carried out with adult students. However, the interview showed that being able to name the phenomenon does not mean that one is able to correctly explain it. In fact, when asked to explain the phenomenon they had identified, some of the interviewees gave answers similar to the ones below:

" (sugar) dissolves in water. Sugar is a solid; in contact with water it changes to liquid; it dissolves" (8th grader, 14 years old);

"The salt dissolves in water; it changes from solid to liquid.... it dissolves.... is transformed.... the cold water dissolves the salt" (8th grader, 14 years).

It seems that naming the phenomenon and identifying the states of matter in each transformation are the best answer for the students and are all they know about it, as they were unable to give further details.

High percentages of students of all academic levels gave answers to the "ball", "car tyre" and "ice" problems which were included in the category "alternative macroscopic explanations", meaning that not only they were unable to use the corpuscular model of matter but also they were unable to correctly explain the phenomena from a macroscopic point of view. Examples of answers in this category given to the "car" problem are presented below:

"The pressure in the car tyres increases during the journey because the tyres get hotter during the journey and therefore get harder." (9th grader, 14 years old);

"The pressure in the car tyre increases because the tyre will dilate as the car moves and therefore the pressure increases." (9th grader, 15 years old).

"Because during the journey the car tyres, when rolling, become warmer and dilate." (8th grader, 13 years old).

The interview revealed that changes in pressure are related to the ideas of stretching and shrinking, as an increase of the pressure was considered to be due to the dilation of the tyre and the tyre was considered to stretch when it dilates. The interview showed mainly that some students used the word pressure but they do not know the meaning of it. In fact, for many students, the pressure in the tyre seems to be a tension in the material of the tyre rather than a force exerted on the tyre by the air. Likewise, most of the alternative macroscopic answers given by the students to the "ball" problem are based on the idea of dilation and contraction of the ball instead of the air inside, as illustrated by the following quotation:

"... when the temperature decreased the ball contracted itself" (8th grader, 13 years old).

Also, some of the students' macroscopic answers to the ball problem seem to include the idea of "heat as a substance" as shown by the following answer (8th grader, 16 years old) and drawing (9th grader, 14 years old):

"The ball was very hard because the heat filled it up completely; when a cooling off takes place the temperature makes the ball less hard." (8th grader, 16 years old).

OxO°xox°
°x°Ox°ox
°Ox°ox°O°

° - particles of heat; O, o, x - particles of air

It is interesting to notice how some students misused the concept of evaporation to explain how the ball became softer, as in the following statement:

"The ball became softer due to the heat because as the heat was decreasing the air inside the ball was slowly evaporating and the ball was becoming more empty" (8th grader, 18 years old).

It might be that this student used evaporation instead of contraction. However, interviews revealed that it may also be that "to evaporate" means "to disappear", as an interviewee put it: "The air evaporated ... the air disappeared from inside the ball" (9th grader, 14 years old), although she could not explain how the air could have disappeared. Maybe the students' reasoning is still that changes in volume require changes in mass, as reinforced by the following statement of one of the interviewees: "The tyre dilates ... the internal space increases and the amount of air must increase" (9th grader, 14 years old).

Regarding the "ice" problem, 50% or more of the students in the three groups gave alternative macroscopic answers. It seems that students believe that whenever ice is submitted to an increase of temperature it

will melt, whatever the final temperature is, as illustrated by the following sample of answers:
"The ice melts when there is an increase of temperature" (9th grader, 17 years old);
"The ice starts melting because it was at a lower temperature" (8th grader, 13 years old).
It could be argued that students gave these answers because they did not realize that the final temperature of the ice was still lower than 0°C. However, the interview showed that students persist in saying that the ice melts (at least in the inside part) even after being told that the melting point of the ice is 0°C (when temperature and pressure are normal).

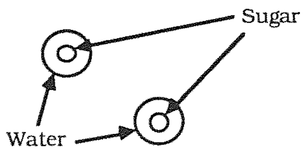
In what concerns the category "empty space", table 2 shows both that some students used the idea of empty space when answering to the "sugar" and "salt" problems and that the highest percentage in this category correspond to 9th graders. The students' performance may be related to the fact that, on average, students' performance on "correct microscopic answers" was higher on "sugar" and "salt" problems than on the other problems, as the empty space based answers are the nearest category of answers when compared with the correct microscopic answers. In fact, the empty space based answers refer to the existence of empty spaces in matter but they do not explicitely refer to particles, as the microscopic answers do.

The percentages of students expressing "alternative microscopic" answers, when responding to the questionnaire, are lower than 10%, meaning that students do not express many alternative ideas about particles. However, these results must be interpreted with caution because students' performance on "correct microscopic" answers is also very low and therefore the low percentages found on the "alternative microscopic" category may mean that students do not know or can not use the concept of particle. Anyway, some alternative ideas were expressed by the students when answering to the questionnaire. The main characteristic of these ideas consists of attributing macroscopic features to microscopic particles, such as: particles can dilate, can contract, can be filled up, can change from one state to another, etc. Examples of this kind of answers are given below:
"With the heat, the molecules of air dilate. After cooling off the molecules return to their normal size and occupy less space inside the ball." (8th grader, 13 years old);
"As the car moves, the particles of the air inside the tyres will start dilating, will start increasing in volume" (9th grader, 14 years old);
"The sugar will be integrated into the particles of water and therefore the water will be sweetened" (8th grader, 16 years old);
"The salt will occupy the empty particles of water and makes the water salty" (8th grader, 15 years old);
"Surely the sugar melts because the water became sweet, because the

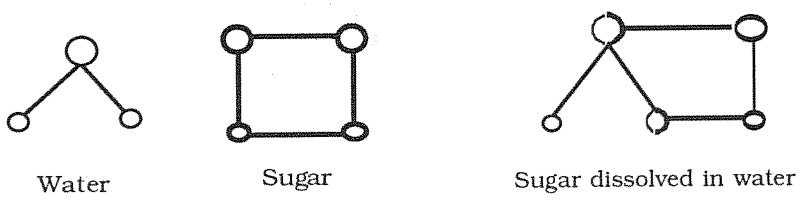
water has particles of air and the sugar went into those particles of air" (9th grader, 14 years old).

In what concerns "contraction of particles", interviews showed that students can either mean a decrease in the size of the particles or a decrease in the space occupied by the particles, that is, a higher concentration of the particles. The same applies to "dilation of particles" but in opposite way.

Relative to the idea of "empty particles" the interviews revealed that some students need this idea to explain dissolution because they apply the macroscopic idea of sweet and salty to the "empty particles" of water. Furthermore, the same students seem to believe that when the water becomes sweet/salty, every particle of the water gets a particle of sugar-salt. If some sugar or salt appears at the bottom of the container it means that every particle of water has a particle of sugar or salt inside it. These ideas may be illustrated by the drawing shown below and done by a 13 years old 8th grader:



Another interesting idea of dissolution was expressed by one interviewee who said:
"The atoms of one, for example sugar, start belonging to the water and vice-versa" (8th grader, 13 years old).
The drawing below was made by the same student:



Regarding the evaporation of water, no alternative idea was found with the questionnaire but the interview revealed that students have some difficulty in explaining how the water changes from liquid to steam as well as how steam goes up and stays in the air, from a particulate point of view. However, it seems that water in the air can behave similarly to sugar or salt in water, as stated by one of the interviewees:
"... water spreads in the air... it can not disappear; it continues in the air... it can penetrate into the molecules of the air" (8th grader, 13 years old).

The difficulty felt in explaining evaporation may be partly due to students' unawareness about forces between particles and motion of the particles as shown by the analysis of both the students' answers to the questionnaire and the interviews. In fact, instead of using the ideas of forces between particles and motion of particles to explain evaporation microscopically, some students preferred to use animistic ideas to do it, as illustrated by the following quotation from one interview:
"... the heat makes the particles separate more and more from each other and, as I said before, makes the particles separate more and more, and they will feel the need to look for more space and make them to change from the liquid state to the gaseous state and when they reach the gaseous state they seem to get satisfaction with that space" (9th grader, 14 years old).

When this student was asked about whether or not the particles of water really change from one state to another, she confirmed this idea although she has stated that she did not know how to explain change more precisely.

The significance of the relationships between all the categories of answers and the groups of students relatively to each problem was tested by the chi-square test and the relationships were statistically significant for the "ball" problem (x^2= 40.826, $p < .0001$), the "sugar" problem (x^2 = 22.635, $p < .05$), the "salt" problem (x^2= 24.856, $p < .05$) and the "water" problem (x^2 = 22.529, $p < .05$). The relationships were not statistically significant for the "car" and "ice" problems.

c. *Students' ideas about the atom*

Regarding the question "What is an atom?", a large variety of answers was found among students, as shown in table 3. Nineth graders are the group of students that performed better (39%) in the category "Two or more of the features" what means that 9th graders gave more answers including two or more features of the atom than each group of 8th graders. Examples of answers in this category are presented below: "An atom is a divisible particle and it is electrically uncharged" (9th grader,16 years old);
"An atom is a very small particle which is invisible and exists in all matter" (9th grader, 14 years old);
"For me, an atom is a particle with a null electrical charge, it is divisible and it is a particle which constitutes matter" (9th grader, 14 years old);
"It is a microscopic particle which constitutes matter. It is constituted by protons, neutrons and electrons" (9th grader, 14 years old).

As these answers include two or more characteristics of the atom, they reveal a better understanding of it than answers which include only one of the features, such as:
"It is a sphere" (8th grader, 12 years old) - *Shape based answer*;
"It is an electrically uncharged particle" (9th grader, 19 years old) - *Charge based answer;*

"It is the fundamental particle of matter" (9th grader, 15 years old) - *Atom as a constituent of matter;*
"It is a very small particle" (9th grader, 15 years old) - *Size based answer;*
"An atom is constituted by protons, neutrons and electrons" (9th grader, 14 years old" - *Structure based answer.*

Table 3 Students' performance on answering to the question "What is an atom ?" (N=182).

Category of answer	8 th grade				9 th grade	
	Regular students (n=58)		Adult students (n=40)		Regular students (n=84)	
	f	%	f	%	f	%
Size based	3	(5)	0	(0)	1	(1)
Shape based	3	(5)	0	(0)	0	(0)
Sctruture based (correct)	1	(2)	2	(5)	11	(13)
Sctruture based (incorrect)	2	(4)	1	(2)	5	(6)
Electric charge based	0	(0)	0	(0)	5	(6)
Atom as constituent of matter	6	(10)	2	(5)	8	(10)
Two or more features mentioned	0	(0)	2	(5)	33	(39)
Atom just a particle	0	(0)	2	(5)	0	(0)
Atom as molecule(s)	8	(14)	3	(7)	7	(8)
Atom as macroscopic thing	1	(2)	9	(23)	0	(0)
Unclassified	17	(29)	5	(13)	6	(7)
Do not Know	17	(29)	14	(35)	8	(10)

It is worth noticing that large percentages of 8th graders (29%, 35%) stated that they do not know what an atom is, despite the fact that they already studied it on their 5th grade. Eighth grade adult students were the ones who gave more answers (23%) including the idea of "atom as a macroscopic thing", what can be related to the fact that most of these students took their 5th grade several years before and probably can remember the word "atom" without any approximate microscopic idea of what it is. Some examples of this kind of answers are given below:
"It is a chemical substance" (8th grader, 35 years old);
"It is an incandescent body" (8th grader, 16 years old);
"It is a body" (8th grader, 13 years old).
On the other hand, 8th grade regular students are the ones who misrelated most the concepts of atom and molecule. In fact, 27% of these students considered that an atom is a molecule or a set of molecules, as they stated in their answers:
"For me, an atom is a set of molecules" (8th grader, 13 years old);
"[Atoms] Are molecules" (8th grader,13 years old);
"An atom is a molecule" (8th grader, 14 years old).

Concerning the structure based incorrect answers, they are mainly due to the fact that students were unable to identify correctly the subatomic particles and/or their place in the atom, as shown by the following example:
"The atom is a thing which has a center (nucleus) with neutrons, electrons and protons moving around the center" (9th grader, 14 years old).
This kind of answers reveals a deficient integration of the ideas taught in school in students' cognitive frameworks, as concepts formally taught in school are improperly related. The interviews seem to indicate that in some cases the kind of science teaching going on in schools does not promote the students task of integrating concepts and can even contribute to students' construction of alternative ideas. In fact, when answering to the question "Are there atoms in the cell?", one of the interviewees stated that:
"No; if there were atoms in the cell the Biology teacher would have told us" (9th grader, 14 years old).
Also, when asked about whether or not living and non living organisms have cells and/or atoms, some interviewees stated that living organisms have cells and non living organisms have atoms. The misrelationship established by the students between "living" and "atom" may be related to the idea that every particle of one substance must have the same properties of the body, as it was already indicated by the "sugar" and "salt" problems. It may also be that students' alternative idea of "atom as a living particle" is reinforced by the fact that atoms are in constant motion and electrons in the atom are permanently moving. An interviewee put it this way:
"The cell is a living particle. the atom is also living; it is inside the cell... As the electrons can move, they are moving, the atom can be a living particle" (9th grader, 13 years old).

Although the interviewees showed a reasonable knowledge about the size and the structure of the atom, some of them still stated that the atom is an indivisible particle which reveals a deficient integration of several pieces of knowledge related to the atom. These alternative ideas concerning the atom and its relationship to living matter have already been found in a previous study carried out by the authors (Sequeira & Leite, 1988) with 228 junior high school students. It seems therefore that the teaching strategies used in school to teach the topic have not been very effective and need to be revised.

4. CONCLUSIONS

The main conclusion drawn from this study is that the majority of the students who participated in the research did not spontaneously use the particulate model of matter to explain everyday phenomena and when some students were asked to do so they seldom succeeded. Another important result of this study concerns the concept of atom which was found to be an ill defined concept for most of the students, even after instruction on chemistry.

A previous study (Sequeira and Leite, 1988a) indicated that more than 50% of the students used particle ideas to explain everyday situations, when the question explicitely contains a reference to particles. This, together with the results of the present study, leads us to question whether or not it is of any good to ask students to use particle theory unless we radically change the teaching strategies on the topic. In fact, this study showed that some stud nts do not find the particulate model more useful than their own models and therefore they do not use it consciously. A main step to change the students' attitudes towards the particulate model seems to consist, first of all, on giving students a better understanding of concepts such as "particle", "atom", "molecule" so that students can both better understand the nature of matter and perceive the particulate model as an intelligible model which can explain everyday situations in a deeper and more comprehensible way than students' models do. However, it seems that it is not worthwhile doing this at the 5th grade level as the students' cognitive development probably does not allow them to acquire such abstract models. Maybe we better teach these models later on, at the 8th grade level and at the same time try to make the integration between the particle ideas with the macroscopic phenomena.

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APPENDIX 1

1. During a very hot day, a football ball was filled up with air until it became very hard. At night, the temperature decreased and the ball became softer. Knowing that the ball did not have any punctures, how can you explain that it became softer?
2. The pressure of the car tyres increases during the journeys. In your opinion, what is the explanation for this fact?
3. An ice block, initially at the temperature of -10°C (minus ten degree centigrade) was taken out of a freezer and its temperature raised up to -1°C (minus one degree centigrade). Describe what happens to the ice due to the increase of its temperature.
4. Imagine you put a spoon of sugar in a glace filled up with water. Describe and explain what happens to the sugar.
5. If you put a spoon of salt in a glass filled up with water, a bit later, all the water in the glass will taste salty. Explain why this happens.
6. If you turn on an electric stove and place on one of the discs an uncovered pot containing water, after a while, there will be no water in the pot. Explain what happened to the water.

STUDENTS' CONCEPTIONS OF THE THREE DIMENSIONS OF THE QUANTITY OF MATTER-VOLUME, MASS AND NUMBER OF PARTICLES: STATIC SYSTEMS

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1. INTRODUCTION

Quantity of matter is measured by mass, volume and number of particles. An understanding of each of these dimensions and the ability to convert from one to another are required for the learning of chemistry. The purpose of this study was to test the ability of students to differentiate between these three dimensions and their ability to qualitatively convert from one to another. This was done in static systems by presenting students with several substances (solids, liquids and gases) of equal quantity in one dimension, and asking them to decide whether or not they were equal in the two other dimensions.

Although the chemist *measures* the quantity of substance by *weighing* it or by determining its *volume*, he or she thinks about it in terms of *particles*. Thus, the quantitative aspect of chemistry deals with three dimensions: two of these - *mass* and *volume* - are physical quantities which can be sensed and directly measured by instruments, and therefore can be considered *concrete*. The concepts of mass and volume are acquired either by experience and intuition or by the learning of physics in school prior to the learning of chemistry. The *third* dimension, which according to IUPAC is named *amount* (of substance) cannot be measured directly by an instrument and cannot be sensed. Thus, in contrast to mass and volume, it is not a concrete concept, but may be regarded as *theoretical*. Students become acquainted with this concept through chemistry lessons rather than by experience or intuition.

The concepts *mass-m* and *volume-v* derive from the concrete macro world and only later in the history of science were they extended to the *micro* world. On the contrary, the concept *amount-n* derives from the micro world and was extended to the *macro* world.

In the course of the learning of chemistry, students are expected to be able to solve stoichiometric problems. A typical stoichiometric school problem might be: "Given a reaction: $aA_{(g)} + bB_{(s)} \rightarrow cC_{(l)} + dD_{(g)}$, how many grams (or moles or liters) of D will be produced if x moles (or grams or liters) of A react?"

In order to solve this problem (which in fact represents 36 different basic variations) the student needs to:

1. understand the meaning of the chemical change;
2. understand the meaning of the chemical language (formulas);
3. differentiate and convert from one dimension of the quantity of matter to another;
4. use proportional reasoning since a proportional relation exists between the reactants and the products.

Many studies (e.g., Ingle & Shayer, 1971; Duncan, 1973; MacDonald, 1975; Novick & Menis, 1976; Dierks, 1981; Umland, 1984; Lazonby, 1985; Lybeck et al., 1988) reveal that students encounter difficulties in solving stoichiometric problems. It is possible that these difficulties originate not only in the need to understand the meaning of the chemical change, chemical language (e.g., Mitchel & Gunstone, 1984; Ben-Zvi et al., 1986) or proportional reasoning but also in the difficulty in differentiating between the three dimensions of the quantity of matter and in converting one dimension to another, especially when both macroscopic and microscopic dimensions are involved.

2. METHOD

Subjects and design

The sample included 66 middle class students from grades nine and ten. The distribution of students according to grade and gender is presented in table 1. Each student was individually interviewed while being shown the materials. Eighteen problems were presented to each of the students. The problems related to all three states of matter (solid, liquid and gas). Israeli students do not deal with the particulate amount of matter and its unit, the mole, until the 10th grade. They are taught about the particulate nature of matter, about elements, compounds and ions, and about basic chemical reactions. We therefore asked about "number of particles" rather than "amount". The 10th grade subjects had studied particulate amount and its unit and had solved stoichiometric problems. Teaching was initiated from the gas laws (Gay-Lussac & Avogadro).

Table 1 Distribution of the research population by grade and gender.

Grade	Boys	Girls	Total
Ninth	20	17	37
Tenth	14	15	29

Tasks

I. Three different known solid objects of equal volume and shape were presented to the student (wood, aluminum and "plastic"). The student was asked to judge:

1. whether they had the same or different mass;
2. whether they had the same or different number of particles. The student was then presented with three different known liquids (water, alcohol and oil) of equal volume (in containers of the same size and shape) and asked:
3. whether they have the same or different mass and to explain his/her answer, and
4. whether they have the same or different number of particles and to explain his/her answer. Finally, the student was presented with three different known gases (O_2, CO_2 and air) of equal volume (in syringes of the same size and shape) and asked:
5. whether they had the same or different mass, and
6. whether they had the same or different number of particles. In each case, the student was asked to explain his/her answer.

II. The following questions were posed to each of the students. If we take equal masses of the three solid objects
7. will they have the same or different volume, and
8. will they have the same or different number of particles. If we take equal masses of the three liquids
9. will they have the same or different volume, and
10. will they have the same or different number of particles. If we take equal masses of the three gases
11. will they have the same or different volume, and
12. will they have the same or different number of particles. In each case the student was asked to explain his/her answer.

III. The following questions were posed to each of the students. If we take an equal number of particles of the three solid objects
13. will they have the same or different volume, and
14. will they have the same or different mass. If we take an equal number of particles of the three liquids
15. will they have the same or different volume, and
16. will they have the same or different mass. If we take an equal number of particles of the three gases
17. will they have the same or different volume, and
18. will they have the same or different mass. In each case the student was asked to explain his/her answer.

3. RESULTS

A. Differentiation and qualitative conversions between the macroscopic dimensions of volume and mass

Table 2 presents the percentage of students who correctly judged the inequality of mass when presented with equal volumes of different substances (solids, liquids and gases). As can be seen from the table students differentiated quite well between volume and mass in this task. The general level of success was 83% correct judgments. It seems that this differentiation was better understood with regard to the solid state than with regard to the liquid state, which in turn was better understood than with regard to the gaseous state. This was especially true in the case of the girls. A significant difference between the performance of boys and girls on the liquid state problems (ANOVA, $p<0.004$) and in the gaseous state problems (ANOVA, $p<0.001$) was found with boys outperforming girls. No significant difference was found between grades except for problems in the gaseous state, where 9th grade students significantly outperformed 10th grade students (ANOVA, $p<0.002$). Students who did not succeed in this task usually explained that "equal volume means equal quantity (or equal number of particles), and therefore the same mass." In the case of problems concerning the gaseous state some students (especially 10th grade boys) said that they had learned the law "equal volumes of different gases have the same mass (or the same number of particles and, therefore, the same mass)." This mistake obviously has its source in what is taught in the chemistry class in the 10th grade. It reflects a confusion between number of particles and mass, and can explain the significant difference in performance between 9th and 10th grade students on problems involving the gaseous state.

Table 2 Percentage of students who correctly judged the inequality of mass when presented with equal volumes of different substances (solids, liquids and gases), by grade and gender.

State of matter	Grade 9 Boys	Grade 9 Girls	Grade 9 All	Grade 10 Boys	Grade 10 Girls	Grade 10 All	Total Boys	Total Girls	Total All
solid (s)	100	94	97	100	100	100	100	97	98
liquid (l)	95	59	78	93	73	83	94*	66	80
gas (g)	100	71	86**	64	40	52	85*	56	71
average of s,l, & g	98	75	87	86	71	79	83*	73	83

* significant difference between boys and girls (ANOVA, $p<0.001$) (in liquid state $p<0.004$ and in gaseous state $p<0.001$, n.s. difference in solid state problems).

** significant difference between 9th and 10th grades in questions in the gaseous state (ANOVA, $p<0.002$) (9th grade outperformed 10th grade).

Explanations of correct judgments could be categorized into three main categories:

1. *different substances have a different mass* (or weight, or heaviness) (9th grade, boys 28%, girls 68%; 10th grade, boys 11%, girls 47%). This explanation was very popular among the girls in both 9th and 10th grade. This category also included explanations referring to the specific properties of the different substances such as: "iron is heavier," etc. This category of explanation, which characterized girls' answers, may indicate a confusion between the extensive quantity of mass and

the intensive quantity of density. In this specific task, such a confusion did not necessarily result in incorrect judgments;

2. *different substances have a different specific weight, or density* (9th grade, boys 67%, girls 19%; 10th grade, boys 53%, girls 16%). This explanation was very popular among boys in both 9th and 10th grades;
3. *different substances have different particles* (or particles of different mass, density, heaviness, etc.) (9th grade, boys 10%, girls 16%; 10th grade, boys 33%, girls 31%). Very few students in the 9th grade used this type of explanation. Its use increased somewhat after the learning of chemistry in the 10th grade in both sexes.

Students' ability to differentiate and qualitatively convert between the two macroscopic dimensions of mass and volume was tested by an additional task. Students were asked to judge the inequality of volume of equal masses of different substances (solids, liquids and gases). Table 3 presents the percentage of students who correctly judged the inequality of volume of equal masses of different substances. Surprisingly, the level of performance on this task (66%) was significantly lower than that on the previous one (83%) (for problems involving the solid state, t-test $p<0.001$; for the liquid state, t-test $p<0.028$; and for the gaseous state, t-test n.s.). As can be seen from the table, a significant difference between the performance of boys and girls was found (ANOVA, $p<0.001$), with boys outperforming girls. No significant difference between grades was found. Students who did not succeed on the task usually explained that the volume of equal masses of different substances are equal because they have the same quantity of matter (or weight, etc.). Explanations of correct judgments could be categorized into three main categories similar to the categories of explanations found in the previous task:

Table 3 Percentage of students who correctly judged the inequality of volume of equal masses of different substances (solids, liquids and gases), by grade and gender.

State of matter	Grade 9			Grade 10			Total		
	Boys	Girls	All	Boys	Girls	All	Boys	Girls	All
solid (s)	85	41	68	93	67	79	88*	53	**71**
liquid (l)	80	47	65	86	53	69	82*	50	**67**
gas (g)	80	50	69	79	29	54	79*	40	**61**
average of s,l, & g	83	46	67	86	50	67	**83***	**48**	**66**

* significant difference between boys and girls (ANOVA, $p<0.001$) (in solid state $p<0.001$, in liquid state $p<0.016$ and in gaseous state $p<0.013$)

1. *the volumes are different because the substances are different* (9th grade, boys 35%, girls 65%; 10th grade, boys 34%, girls 69%). This explanation was very popular among the girls in both 9th and 10th grades, but more boys offered it here than in the previous task. This category also included explanations which related to the previous task

if equal volumes had different masses than equal masses should have different volumes" or "mass and volume are different quantities") and explanations relating to the specific properties of the substances.

2. *the volumes are different because each substance has a different specific weight or density* (9th grade, boys 49%, girls 17%; 10th grade, boys 31%, girls 0%). This explanation was popular among boys in both 9th and 10th grade but not to the same extent as in the previous task.
3. *the volumes are different because each substance has different particles* (9th grade, boys 10%, girls 9%; 10th grade, boys 25%, girls 14%). Very few students used his explanatory in either the 9th or the 10th grades.

B. Differentiation and qualitative conversions between the macroscopic dimension of mass and the microscopic dimension of number of particles

Table 4 presents the percentage of students who correctly judged the inequality of mass of an equal number of particles of different substances (solids, liquids and gases). As can be seen from the table in this task students differentiated quite well between the macroscopic dimension of mass and the microscopic dimension of number of particles. The general level of success was 82%. Interestingly, no significant difference between either the grade or the sex of the subjects was found. Only on problems involving the liquid state did 10th grade girls outperform 10th grade boys (ANOVA - significant interaction of grade and sex $p<0.012$). Problems in the gaseous state seem to have been more difficult than problems in other states of matter for 10th grade girls. This is probably a negative result of the learning of chemistry in the 10th grade. Students had studied that equal volumes of different gases have the same number of particles, and they extended this knowledge to mass. Students who did not succeed in this task usually explained that equal numbers of particles contain equal quantities (or volumes) of matter and therefore have the same mass. The few students who did this apparently confused the different dimensions of matter. Explanations of correct judgments could be categorized into three main categories.

Tabel 4 Percentage of students who correctly judged the inequality of mass of equal number of particles of different substances (solids, liquids and gases), by grade and gender.

State of matter	Grade 9 Boys	Grade 9 Girls	Grade 9 All	Grade 10 Boys	Grade 10 Girls	Grade 10 All	Total Boys	Total Girls	Total All
solid (s)	88	76	82	85	92	86	87	83	85
liquid (l)	88	76	82	77	92*	85	83	83	83
gas (g)	94	82	88	77	54	65	86	70	78
average of s,l, & g	90	78	84	80	79	79	85	79	82

* significant interaction between grade and sex (ANOVA, $p<0.012$)

1. *the masses are different because the substances are different* (9th grade, boys 4%, girls 27%; 10th grade, boys 6%, girls 38%).
2. *the masses are different because the different substances have different densities or specific weights* (9th grade, boys 38%, girls 15%; 10th grade, boys 13%, girls 3%).
3. *the masses are different because the particles of each substance are different* (or have different size, mass or weight) (9th grade, boys 51%, girls 45%; 10th grade, boys 58%, girls 48%).

This was the most popular explanation among all groups.

Students' ability to differentiate and qualitatively convert between the macroscopic dimension of mass and the microscopic dimension of number of particles was tested by an additional task. Students were asked to judge the equality or inequality of the number of particles of equal masses of different substances (solids, liquid and gases). Table 5 presents the percentage of students who correctly judged the inequality of the number of particles of equal masses of different substances. Surprisingly, the level of performance on this task (66%) was significantly lower than that on the previous one (82%) (in problems in the solid state t-test $p<0.006$; in problems in the gaseous state, t-test $p<0.001$).

As can be seen from Table 5 boys consistently outperformed girls (in problems in the solid state; the difference is significant $p<0.050$, in the liquid state $p<0.090$ and in the gaseous state $p<0.080$). A significant difference was observed between grades for problems in the gaseous state in favor of the 9th grade students. Problems in the gaseous state seem to have been more difficult than problems in other states of matter for 10th grade students (boys and girls). This is another expression of the negative effect of the learning of chemistry in the 10th grade. Learning about the relationship between the volume of gases and the number of particles seems to confuse students in their judgments about the relationship between mass and number of particles. Students who did not succeed in this task usually explained that the number of particles of equal masses of different substances is the same because they have the same quantity (or weight or mass or volume) of matter.

Table 5 Percentage of students who correctly judged the inequality of the number of particles of equal masses of different substances (solids, liquids and gases), by grade and gender.

State of matter	Grade 9 Boys	Grade 9 Girls	Grade 9 All	Grade 10 Boys	Grade 10 Girls	Grade 10 All	Total Boys	Total Girls	Total All
solid (s)	68	47	58	85	67	75	75*	56	66
liquid (l)	79	69	74	86	60	72	82	65	73
gas (g)	80	56	69**	57	36	46	71	47	59
average of s,l, & g	76	57	67	76	54	64	76	56	66

* significant difference between boys and girls in solid state problems (ANOVA $p<0.050$)

** significant difference between grades in gaseous state problems (ANOVA $p<0.054$)

Explanations for correct judgment could be divided into the same three categories, as above:

1. *the number of particles of equal masses of different substances is different because the substances are different or because their volume or quantity is different* (this is based on the previous task which dealt with mass and volume) (9th grade, boys 39%, girls 64%; 10th grade, boys 38%, girls 50%). This type of explanation was much more popular in this task than in the previous one, both among boys and girls and in both grades;
2. *the number of particles is different because the densities or the specific weights of the different substances are different* (9th grade, boys 9%, girls 11%; 10th grade, boys 10%, girls 4%);
3. *the number of particles is different because the particles of each substance are different* (or have different mass, volume, etc.) (9th grade, boys 34%, girls 11%; 10th grade, boys 35%, girls 29%). This type of explanation was used much less frequently in this task than in the previous one, especially by the girls. Some of the students who related to the difference in the particles referred to the distances between them rather than to their different masses. It is interesting to note that no difference in the distribution of this explanation between the grades was observed.

C. Differentiation and qualitative conversion between the macroscopic dimension of volume and the microscopic dimension of number of particles

Table 6 presents the percentage of students who correctly judged the equality or inequality of the number of particles of equal volumes of different substances (solids, liquids and gases). In this set of problems, the gaseous state is unique as equal volumes of different gases have the same number of particles (unlike the other states of matter). As can be seen from the table, students had difficulty in differentiating and converting between volume and number of particles. The general level of success

Table 6 Percentage of students who correctly judged the equality of the number of particles of equal volumes of different substances (solids, liquids and gases), by grade and gender.

State of matter	Grade 9 Boys	Grade 9 Girls	Grade 9 All	Grade 10 Boys	Grade 10 Girls	Grade 10 All	Total Boys	Total Girls	Total All
solid (s)	60	76	67	71	67	69	65	72	68
liquid (l)	75	47	62	79	60	69	76*	53	65
gas (g)	16	47	31	64	60	62**	36	53	45
average of s,l, & g	50	57	53	71	62	67	59	59	59

* significant difference between boys and girls (ANOVA $p<0.029$)

** significant difference between grades (ANOVA $p<0.015$)

was only 59%. It seems that boys performed significantly better than girls on problems in the liquid state (ANOVA, $p<0.029$) and 10th grade students significantly outperformed 9th grade students on problems in the gaseous state (ANOVA, $p<0.015$). This is very understandable since there is virtually no chance of succeeding in this task without having studied the relevant gas laws. The relatively high performance of 9th grade girls on this task is of interest. Ninth grade boys judged the gases in the same way as they did the liquids, and thus gave incorrect answers, while many 9th grade girls misjudged the liquid problems, thinking that equal volumes of different liquids had the same number of particles, and so unintentionally correctly judged the gases. Students who did not succeed in the solid or liquid state problems usually claimed that since the volumes of the different substances are equal, they should also have the same number of particles. Few used Avogadro's law or number in explaining their incorrect judgments. Explanations for incorrect judgments of problems in the gaseous state usually related to the difference in the particles (their volume or density) of the different gases and probably originated from the extension of knowledge regarding solids and liquids.

Explanations of correct judgments of the solid and liquid state problems could be divided as before to three main categories:

1. *the number of particles is different because the substances (or their quantity or mass) are different* (9th grade, boys 18%, girls 50%; 10th grade, boys 0%, girls 37%);
2. *the number of particles is different because the densities or concentrations of particles (or the distances between them) are different* (9th grade, boys 22%, girls 18%; 10th grade, boys 63%, girls 26%);
3. *the number of particles is different because the particles (or their volume) are different* (9th grade, boys 44%, girls 14%; 10th grade, boys 31%, girls 26%).

Explanations for correct judgments of the problems in the gaseous state were:

1. *the number of particles is equal because the volumes are equal.* This explanation was popular among 9th grade girls (56%). Those who offered this explanation had usually also used it to justify their incorrect judgment in the problems involving the solid or liquid state. It was used much less frequently by 9th grade boys (33%) and 10th grade girls (33%) and boys (14%);
2. *the number of particles is equal because the densities or pressures or compressibilities of all the gases are similar.* This kind of explanation was used only in the 9th grade (boys 33%, girls 37%);
3. *the number of particles is equal because all of the substances are gases.* This type of explanation was not very popular among any of the groups of subjects (9th grade: boys, 33%, girls 13%; 10th grade: boys 14%, girls 0%);
4. *the number of particles is equal because in gases equal volumes of different gases have the same number of particles.* This type of explanation appeared sometimes to be rote learning and was at times

followed by an explanation of the law. As expected, it was used only by the 10th grade (boys 71%, girls 66%).

Students' ability to differentiate and qualitatively convert between the macroscopic dimension of volume and the microscopic dimension of number of particles was also tested by an additional task. Students were asked to judge the equality or inequality of the volume of different substances (solids, liquids and gases) where the number of particles was equal. Table 7 presents the percentage of students who correctly judged the equality and inequality of the volumes of equal number of particles of different substances. As expected, the level of performance in both tasks was similar but relatively low (59% and 56%). This finding suggests that students have difficulty in differentiating and converting between volume and number of particles, especially with regard to gases. As already mentioned, the relevant behavior of gases is different from that of solids and liquids, and this may explain the difficulty encountered in these tasks.

Table 7 Percentage of students who correctly judged the equality or inequality of the volumes of equal number of particles of different substances (solids, liquids and gases), by grade and gender.

State of matter	Grade 9 Boys	Grade 9 Girls	Grade 9 All	Grade 10 Boys	Grade 10 Girls	Grade 10 All	Total Boys	Total Girls	Total All
solid (s)	65	53	59	62	69	65	63	60	62
liquid (l)	65	41	53	69	61	65	67	50	58
gas (g)	25	47	36	54	77	65*	38	60	49
average of s,l, & g	52	47	49	62	69	65	36	57	56

* significant difference between grades (ANOVA, $p<0.034$)

As can be seen from the table no significant difference between boys and girls was found. However, a significant difference was found between grades 9 and 10 with regard to problems in the gaseous state (ANOVA, $p<0.034$), revealing that after learning the performances of both boys and girls significantly improved. The relatively high performance of 9th grade girls in problems in the gaseous state resembles their performance in the previous task and probably has the same origin: while boys failed because they extrapolated their correct knowledge of solids and liquids, girls inappropriately extrapolated their incorrect knowledge of solids and liquids and unintentionally provided the correct answer in regard to gases. Students who did not succeed in the solid or liquid state problems usually claimed that since the number of particles of the different substances was

Explanations of correct judgments of the solid and liquid state problem could be categorized into three main categories, as before:

1. *the volumes of the different substances are different because the substances (or their quantity) are different* (9th grade, boys 9%, girls 12%; 10th grade, boys 13%, girls 23%).
2. *the volumes of the different substances are different because the densities (or distances between particles) are different* (9th grade, boys 18%, girls 25%; 10th grade, boys 7%, girls 16%).
3. *the volumes of the different substances are different because the particles (or their volume or mass) are different* (9th grade, boys 64%, girls 50%; 10th grade, boys 53%, girls 53%). This was the most popular explanation among all groups of students.

Explanations for correct judgments of the problems in the gaseous state were:

1. *the volumes are equal because the number of particles are equal.* This explanation was given mostly by ninth grade students;
2. *the volumes are equal because in gases the distances between particles are so large that the particle volume can be disregarded.* It is interesting that in this task students did not use the law as it was formulated in class but rather explained it physically. This may result from the fact that the formulation of the law states that: "equal volumes of different gases contain the same number of particles" and not "an equal number of particles of different gases occupy the same volume."

4. DISCUSSION

The results presented in this paper indicate that 9th and 10th grade students are able to differentiate and qualitatively convert between the macroscopic dimensions of the quantity of matter (volume and mass) and between the macroscopic dimension of mass and the microscopic dimension of number of particles in some of the tasks presented to them. However, they have difficulty in performing the same operations with regard to other, essentially similar and logically related, tasks. The level of success in judging the inequality of mass of equal volumes of different substances was 83%, while the level of success in judging the inequality of volume of equal masses of different substances was significantly lower - 66%. Similarly, the level of success in judging the inequality of mass of an equal number of particles of different substances was 82%, while the level of success in judging the inequality of the number of particles of equal masses of different substances was significantly lower - 66%. This finding can be understood if we assume that students' difficulties in solving stoichiometric problems are related neither to their inability to differentiate between the different dimensions of the quantity of matter, nor to their need to shift between the macroscopic and the microscopic levels, but rather to the different reasoning processes required in solving the different tasks. The conversion from volume to mass ($v \rightarrow m$) and from number of particles to mass (N→m) requires direct ratio reasoning: for the substances 1 and 2, $m_1/v_1 = d_1$ and $m_2/v_2 = d_2$. If $v_1=v_2$ and $d_1>d_2$ then $m_1>m_2$; for the same substances $m_1/N_1=Mee_1$ and $m_2/N_2=Mee_2$. If $N_1=N_2$ and $Mee_1>Mee_2$ then $m_1>m_2$. The conversion from mass to volume (m→v) and from mass to number of particles (m→N) requires inverse ratio reasoning: For the substances 1 and 2 $m_1/v_1=d_1$ and $m_2/v_2=d_2$. If $m_1=m_2$ and $d_1>d_2$ then $v_1<v_2$. For the same substances $m_1/N_1=Mee_1$ and $m_2/N_2=Mee_2$. If $m_1=m_2$ and $Mee_1>Mee_2$ the $N_1<N_2$. It has been shown that for young children direct ratio reasoning is much easier than inverse ratio reasoning (e.g., Stavy, 1981), but it was not expected that older students of the age of 15-16 would have the same difficulty especially in this case of qualitative tasks. Although each pair of tasks (m→v, v→m) is logically identical and one could represent the "inverse ratio" problems in terms of direct ratio e.g. v/m=constant (or N/m=constant for the pair m→N, N→m), students apparently prefer to use that ratio which has an intuitive meaning. The ratio m/v represents density or "heaviness" of a substance - a property which can be intuitively grasped and visualized, whereas the ratio v/m has no immediate meaning and cannot be similarly grasped and visualized. The same is true with regard to the conversions between mass and number of particles (N→m, m→N). While the ratio m/N has a meaning - the mass of one particle, and thus can be easily grasped and mentally visualized, the ratio N/m has no such immediate meaning and is therefore difficult to grasp or to see with the mind's eye. Support for this explanation can be found in the students' explanations of their judgments. In the conversion from volume to mass they used the idea of density or heaviness to a larger extent than in the conversion from mass to volume; in the conversion from number of particles to mass they used more the idea of particle mass more frequently than in the conversion from mass to number of particles. The question then arises as to why no such difference was found between the two tasks involving conversion between volume and number of particles? These two tasks showed a lower level of success resembling that of the inverse ratios in the other conversions (59% and 56%). It is possible that in this case the direct ratio in itself - v/N is a more difficult quantity to grasp because molar volume is affected by both the volume of the particles and the distances between them. These distances change from substance to substance with the state of matter, with temperature, pressure, etc. In addition, the behavior of gases is different than that of solids and liquids. In gases at S.T.P, molar volume is dependent only on the distances between particles and is equal for all gases. Indeed the hardest tasks in this conversion were those relating to gases. It is clear that before learning, students cannot be expected to know and understand these issues. It was shown that learning significantly improved students' performance on these tasks, but even after learning in the 10th grade the level of performance was still not very high.

Another interesting finding is that, in general, performance on tasks involving solids was higher than on tasks involving liquids which in turn was higher than on tasks involving gases. Students' difficulties on the gaseous state problems can be attributed also to their difficulty in conceiving of gases as materials (Stavy, 1988).

A very significant difference between the performance of boys and girls was observed, with boys consistently outperforming girls (for all tasks: ANOVA, $p<0.005$). Sex-related differences, favoring boys, have been reported for several Piagetian tasks that are related to concepts and topics in the science curriculum (Howe & Shayer, 1981; Linn & Polus, 1983; Robert, 1989). It has been suggested that this difference is due to an experiential deficit on the part of the girls or to an underlying difference in cognitive structure or style. Although we cannot explain the observed difference between boys and girls in our study, we can suggest that it may be related to girls' inferiority in spatio-visual abilities (Liben, 1978). Our tasks, if not worked out on a formal mathematical level alone, require some manipulation of mental images.

Another important point that should be raised is the ineffectiveness of teaching. No significant differences were observed between 9th and 10th grade students (except for the problems demanding conversion between volume and number of particles). It seems that in the course of chemistry teaching, insufficient attention is paid to the serious problems which students (especially girls) have with the basic concept of the quantity of matter.

Educational Implications

Our recommendations, based on these findings, are as follows.

1. Introduce the particulate amount, n concept and its unit the mole, as a third dimension of the quantity of matter: its definition can be based on a pile of particles and the unit presented as a certain arbitrary number (N_A) which has a different mass for each substance, Molar mass (Mm).
2. After introducing the mole unit, it is advisable to "ignore" its micro level and to avoid problems of the sort: "How many molecules or atoms (particles) are in X moles (or grams) of a certain substance?" Instead, it is important to start to practise the conversion $n \rightarrow m$ on the macro level (since this was found to be the easiest conversion for students). The next step is to practise both directions $n \Longleftrightarrow m$ on the macro level. The problems on the macro level are important in order to attribute the same "status" to "amount" as to other physical dimensions (mass and volume).
3. Starting conversions in the solid state and postponing problems which deal with volume and gases.
4. Not relying on the students' knowledge or ability to convert $m \rightarrow v$ and to practise these conversions prior to or during the study of chemistry, starting with $v \rightarrow m$ in the solid state and emphasizing the inverse ratio aspect.
5. Emphasizing the analogy between density (d); Molar mass (Mm) and molar volume (Vm) as characteristic (Vm for all gases is the same at

the same pressure and temperature) intensive properties of substances.
6. Emphasizing the equivalence between the three dimensions, volume, mass and amount (particulate), as properties on which we can base our measurements of a given quantity of substance.

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STUDENTS' RESPONSES TO AN ACTIVE LEARNING APPROACH TO TEACHING THE PARTICULATE THEORY OF MATTER

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1. STUDENTS' IDEAS ABOUT THE NATURE AND BEHAVIOUR OF MATTER

There is a substantial body of research which suggests that children of all ages have beliefs about the nature and behaviour of matter which conflict with the school science view. A cross-age study of students from four to twelve years old, reported by Piaget and Inhelder (1974), suggests that while many students below the age of ten hold the view that matter is continuous, children do begin to develop an atomistic view of matter with increasing age.

Other research (e.g. Brook, Briggs & Driver, 1984; Happs, 1980; Wightman, 1986) suggests, however, that many older students also hold the view that matter is continuous, or are ready to use particulate/kinetic theory only within very limited contexts.

It also seems to be the case that, even when students appear to accept that matter is made of particles, many hold a range of alternative views about the nature and behaviour of these particles. For example students hold a variety of ideas about the nature of the particles themselves (Dow, Auld & Wilson, 1978; Happs, 1980). It is also common for students to attribute microscopic properties (such as melting or expanding) to particles (Brook, Briggs & Driver, 1984; Briggs & Holding, 1986; Happs, 1980; Wightman, 1986) or to construct alternative interpretations of kinetic theory. (Reported ideas include the notion that there is air in the gaps between gas particles; Nussbaum & Novick, 1981; Brook, Briggs & Driver, 1986; Wightman, 1986; and confusion about the motion of particles in solid, liquid and gaseous states, often with a lack of appreciation of the intrinsic motion of particles; Novick & Nussbaum, 1981; Wightman, 1986).

There is evidence to suggest that many students continue to hold on to their alternative ideas about the nature and behaviour of matter even after formal teaching about the particulate/kinetic theory of matter (Brook, Briggs & Driver, 1984). In the light of this evidence, the Children's Learning in Science Project developed a teaching scheme which was intended to address directly some of these ideas and to encourage students to reject them in favour of the school science view.

2. A TEACHING SCHEME ON THE PARTICULATE NATURE OF MATTER

The teaching scheme described in this paper was developed by the Children's Learning in Science Project in collaboration with a group of twelve high school science teachers. The scheme was developed with reference to a constructivist perspective on learning, where learners are seen as making sense of the world by continually constructing mental models of the world which they use to anticipate and interpret events. Already existing mental models are used to make links with, and make sense of, new experiences (Carey, 1985; Brook, Driver & Johnston, 1987). In the classroom setting, meaningful learning will involve students in developing, modifying and changing their existing mental models or concepts.

A number of mechanisms for learning as conceptual change have been suggested (e.g. Posner, Strike, Hewson & Gertzog, 1982; Nussbaum & Novick, 1982; Osborne & Wittrock, 1985), and some authors report on trials of teaching/learning strategies designed to promote conceptual change in science classrooms (e.g. Nussbaum & Novick, 1982; Hewson & Hewson, 1981; Brown & Clement, 1987). Driver (1989) reviews some of the classroom strategies which have emerged from such work, but suggests that in designing teaching strategies to promote conceptual development it may be necessary to look beyond general theories of conceptual change: "....it has been necessary to consider the nature of the learner conceptions and how they differ from the learning goals in order to identify appropriate pedagogical strategies. This leads to the suggestion that strategies for promoting conceptual change need to be investigated in the context of particular domains of knowledge. General prescriptions of the conceptual change process itself are not enough; information about the nature of the change to be promoted is necessary in designing instructional sequences".

The teaching scheme is based on a generalised teaching sequence proposed by Driver and Oldham (1986). This generalised sequence consists of the following:

An elicitation phase: Where students are provided with opportunities to put forward their own ideas and to consider the idea of their peers.

A restructuring phase: Where the teacher introduces activities which interact with students' prior ideas and which encourage students to move their thinking towards the school science view.

A review phase: Where students are asked to reflect on the ways in which their ideas have changed.

The scheme itself was designed for use with 13-14 year old students of a wide range of abilities, and addresses the following areas of content:

- all substances (not just "scientific" ones) are made of atoms/particles;
- atoms/particles are very small;

- atoms/particles are arranged/spaced in certain ways in solids, liquids and gases;
- there are forces of attraction between atoms/particles and these are different in solids, liquids and gases.

It was hoped that at the end of the teaching scheme students would feel confident in attempting to explain some simple phenomena relating to the behaviour of solids, liquids and gases using particulate ideas. The scheme itself consists of nine or ten 70 minute lessons, although there is some flexibility within it. It is divided into six sections, each of which is now described briefly.

Elicitation of students' ideas: Students are asked for their own ideas about a number of simple phenomena relating to the behaviour of matter.

The nature of scientific theories and theory generation: Through games and discussion students are encouraged to reflect on their own understandings of theories and how they are developed.

A pattern of properties for solids, liquids and gases: Students put forward their own ideas about the properties of solids, liquids and gases, and, with the help of the teacher, try to reach a consensus view on a pattern of properties.

Theory making: Students are asked to draw on discussions held in earlier lessons as well as their own ideas, in putting forward theories to explain the nature and behaviour of solids, liquids and gases.

Review, reflection and movement towards the school science view: The theories put forward by students are reviewed by the class. The teacher then introduces activities which address some of the issues raised by students, and which are designed to help students develop and change their ideas.

Application of the school science view: Students are asked to use the school science view of the particulate theory of matter to explain a number of phenomena. They are also asked to reflect on how their own ideas have changed since the Elicitation Lessons.

Data on the implementation of the scheme were collected from a total of 13 classrooms, and include the following:

- Pre and post teaching diagnostic tests (reported elsewhere; Johnston, 1990);
- Classroom observations using field notes and audiotapes of both teachers and students;
- Audiotapes of interviews with students (individuals and groups);
- Written material produced by students.

3. AN ANALYSIS OF THE SCHEME IN ACTION

Elicitation of students' ideas

In the first section of the scheme students work in pairs, examining a range of phenomena relating to the properties of matter. They carry out simple practical tasks, make observations and put forward their own explanations for these observations. Ideas are recorded on worksheets and then students work in groups of four or five to produce posters recording some of their ideas for display to the rest of the class. The tasks themselves are designed to explore students' ideas about phenomena such as diffusion, compressibility and density differences between solids, liquids and gases.

At this stage in the scheme, the following general features of students' ideas about the nature and behaviour of matter can be identified from their response to the tasks.

a. In almost every class participating at the trials of the scheme (and for students of all abilities) *some* students attempted to explain *some* of the tasks using ideas about atoms/particles. However, individual students showed little consistency in the ways in which they used such ideas, many using particulate ideas to explain one phenomenon but other ideas for other phenomena. Very few students freely volunteered the origins of such particulate ideas, but when questioned about them some mentioned earlier teaching (often at elementary school), television programmes and books.
b. Many students failed to move beyond the descriptive in their written responses. It was common when writing explanations for students to simply repeat or rephrase their observations.
c. Students appeared to hold alternative meanings for a number of scientific words such as weight, density, area, volume, melt, evaporate and energy.
d. There was a tendency for students to draw on everyday rather than school science experiences in constructing their explanations. This may in part have been due to the nature of the tasks themselves, some of which made use of everyday materials.

A brief description is now given of one task and students' responses to it.

The "Blocks" task simply consists of two objects of the same dimensions but made of materials with contrasting densities (e.g. blocks of aluminum and lead). Students are asked to note both similarities and differences between the blocks and to try to explain their observations. Most students made observations relatively to the size and shape of the blocks, noting that in some ways they were very similar. Most also noted the difference in density. A significant number of students also recorded other observations, for example the colour and texture of the blocks.

In attempting to put forward explanations many students simply re-iterated their observations. A smaller number speculated that the difference in density might be related to something inside the blocks, and of these, some put forward particulate ideas, suggesting either that the "heavier" block contained "heavier" particles or that the particles in the "heavier" block must be packed more closely together. These two boys are discussing a block of iron and a block of perspex.

Darren: So what we're really saying is we think the particles are spread out in one, and bunched up in the other.

Clive: Yes, so it's obvious, they're different weights and the only way they can be different weights is different materials - and particles - all the particles could be bunched up or spread out.

Several students suggested that if particles were spread out in the less dense block there might be air in gaps between the particles. They described air as being "light" or having negative mass, and argued that it would contribute to the "lightness" of the less dense block. Figure 1 illustrates a poster produced by a group in response to the "Blocks" task.

The Nature of scientific theories and theory generation

This section of the scheme is designed to provide students with opportunities to reflect on the following issues in relation to scientific theories:

- data can be sorted out or arranged in patterns
- scientific theories are products of the human imagination
- scientific theories are not absolute: they are open to revision and change.

Discussion and reflection are encouraged by use of a number of theory making games, set in non-scientific contexts. While students enjoyed playing these games, many had difficulty in making links between the games and scientific activities. A more detailed analysis of this section of the scheme is presented elsewhere (Johnston, 1990).

A Pattern of Properties for Solids, Liquids and Gases

This section of the scheme examines students' own ideas about the properties of solids, liquids and gases and the relationships between them. Firstly, students are asked individually to classify a range of substances as either solid, liquid or gas. For most students this exercise proved to be non-problematic:

"The way I worked out the ones I was not sure about, like cloth, it didn't seem solid, but it wasn't gas and it wasn't liquid so it must have been solid. I don't see how people can get them wrong if they work them out like I do." (Darren).

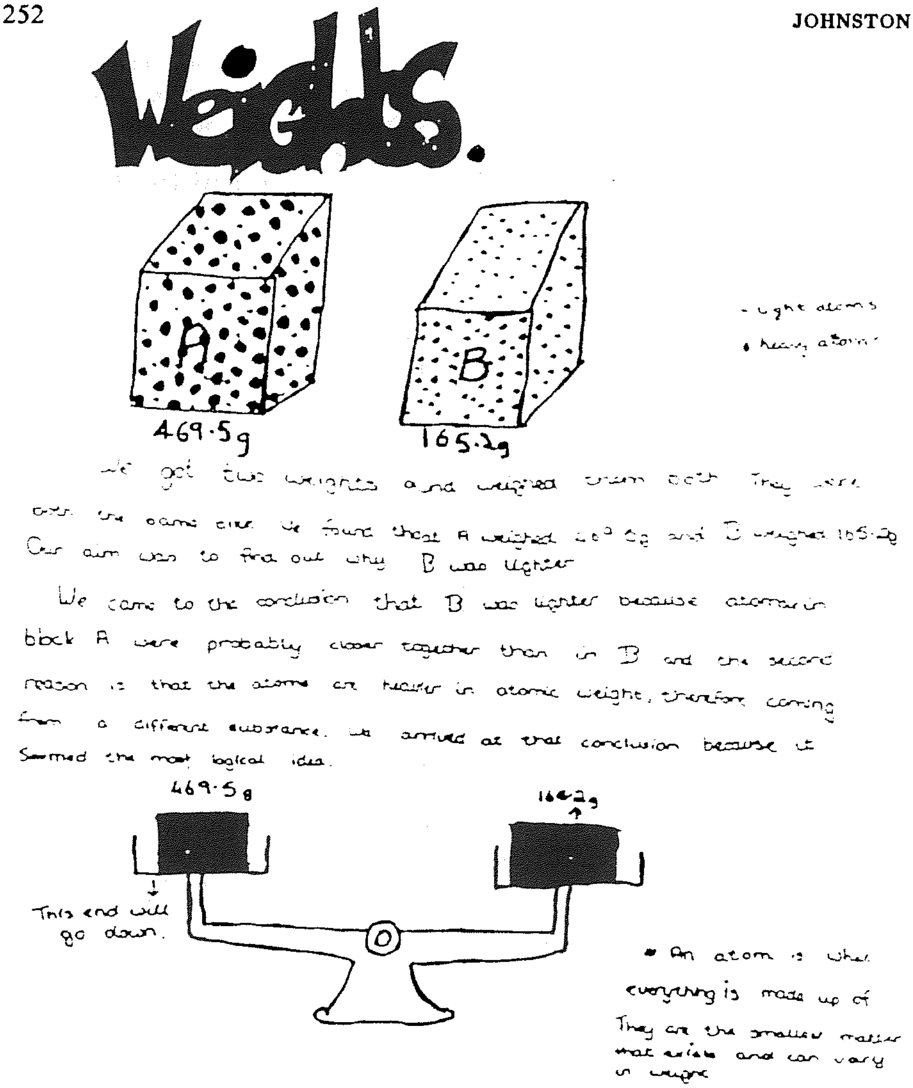
Working in groups, they are asked to identify the criteria which they use to classify substances as solid, liquid or gas: how do they *know* that wood is a solid rather than a liquid or a gas? For most students this exercise proved to be quite difficult, as the following comments illustrate:

"I suppose knowing what a thing is is taken for granted because explaining this was very difficult". (Shirley)

"We found it quite hard, we kept disagreeing". (Sean)

"I can't decide.....it's just one of those things you know". (Yogendra)

Ideas commonly put forward by groups included the following.

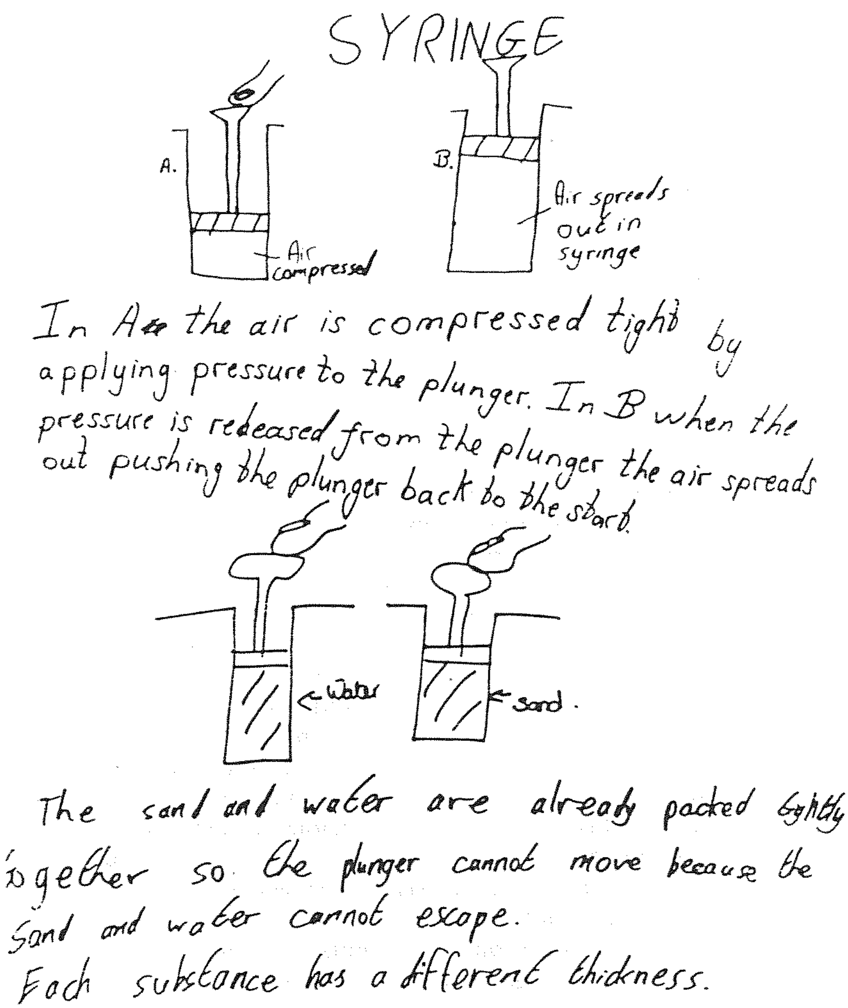


"We got two weights and weighed them both. They were both the same size. We found that A weighed 469.5g. and B weighed 165.2g. Our aim was to find out why B was lighter.

We came to the conclusion that B was lighter because atoms in block A were probably closer together than in B and the second reason is that the atoms are heavier in atomic weight, therefore coming from a different substance. We arrived at that conclusion because it seemed the most logical idea."

"* An atom is what everything is made up of. They are the smallest matter that exists and can vary in weight."

Fig. 1a Posters Produced by Groups: "Blocks" Task.



"In A the air is compressed tight by applying pressure to the plunger. In B when the pressure is released from the plunger the air spreads out pushing the plunger back to the start."

"The sand and water are already packed tightly together so the plunger cannot move because the sand and water cannot escape. Each substance has a different thickness."

Fig. 1b A "Syringes" Poster.

Solids: School science ideas included comments about density (usually referred to as "weight") fixed shape and non-compressibility. Other ideas included: solids are visible, solids are dry, solids are usually hard.

Liquids: School science ideas included: liquids take the shape of the container, ideas about density and compressibility. Other ideas included: liquids are wet, liquids are cold, liquids are easy to shake, liquids can be compressed.

Gases: Many groups encountered problems in trying to explain the criteria which they used to identify gases. School science ideas included notions of low density, compressibility and diffusion. Other ideas were: gases "weigh nothing" or have negative mass, gases are invisible, gases have no feel or texture.

After groups discuss their own criteria the teacher collects together the data from all groups and in a class discussion attempts to negotiate a consensus "Pattern of Properties" for solids, liquids and gases. In practice, negotiation took different forms in different classes. Some teachers, concerned by the gaps between students' own ideas and the school science view, intervened in a direct way, correcting students use of scientific words, introducing new terms (e.g. diffusion, compression) and indicating that some of the ideas put forward by groups were not appropriate. Other teachers continued to try to work from students' ideas, attempting to provide opportunities for students to explore each idea for themselves (a time consuming process). This is the first point in the teaching scheme where the teacher is faced with the choice between continuing to work with students ideas or making an input of "school science". Figure 2 illustrates two final versions of the pattern of properties: in class A the teacher had continued to work from students' ideas, using students' own language; in class B the teacher had made a greater input of school science ideas.

In summary, an examination of students' responses to this section of the teaching scheme highlights the gap between school science ideas and the everyday experiences of students. Many of the ideas which students put forward relate to life world experiences, where for example, a "solid" is not seen as a dense object with a rigid shape, and where gases barely impinge on our awareness. It also became apparent that (as already noted in relation to the Elicitation section of the scheme) students did not appear to see the need for comparisons across contexts. Many appeared to consider solids, liquids and gases as separate categories with their own unique sets of properties, and did not spontaneously make comparisons between them.

Student theory making

In the central lesson of the teaching scheme, groups of students are asked to generate *one* theory which would explain what solids, liquids and gases are like inside, and why they behave in the ways described in the pattern of properties. The teacher reminds students of discussions which

CLASS A

PROPERTY	SOLID	LIQUID	GAS
HEAVINESS	HIGH/LOW	HIGH/LOW	LOW
STRENGTH	STRONG	A LITTLE STRENGTH	NONE
SQUASHINESS	NONE	A LITTLE/ NONE	A LOT
SHAPE	FIXED	OF CONTAINER	NONE, IT SPREADS

CLASS B

PROPERTY	SOLID	LIQUID	GAS
SHAPE	DEFINITE	OF CONTAINER	FILLS CONTAINER
STRENGTH	STRONG SUPPORT THEMSELVES	LIMITED	NO STRENGTH
DIFFUSION	NEGLIGIBLE	SLOW	FAST
COMPRESSIBILITY	LIMITED	CAN'T BE	SQUASHY
DENSITY	HIGH	A LITTLE LESS	VERY LOW

Fig. 2 The Pattern of Properties: Final Versions from Two Classes.

have taken place in previous lessons (both about the nature and behaviour of matter and about the nature of scientific theories), and encourages them to also draw on ideas from outside school science lessons. Each group illustrates its ideas on a poster (examples given in figure 3). Some groups found this task difficult to begin, and in a few cases teachers had to explain what was required several times before students were able to start their discussions. Once discussions started, however, most students appeared to participate actively and seemed well motivated by the task. Many groups started to talk in particulate terms almost immediately, though some did not progress beyond macroscopic descriptions. In all classes however (even those of less able students) at least one group produced a poster showing some particulate ideas, and in most classes such ideas were used by the majority of groups. A brief summary of the main ideas put forward is now given.

a. *Particle position and separation.* The spatial arrangement of particles was the key feature on many posters with a large number of groups displaying some understanding of the school science view. Some students, however, argued that the spatial arrangement of particles in liquids was intermediate between solids and gases. This idea was often linked with a view that liquids can be compressed: "....particles in a solid are so close together it cannot be compressed, because there is no space in between the particles. The particles in a liquid are a little further apart. This means the particles have a little more room to be compressed into. The particles in a gas can be compressed because there is a lot more space between the particles". (Sarah)
b. *Size and shape of the particles.* Most students envisaged the particles as being very small, though for many this meant microscopic. Several students confused particles/atoms/molecules with things which they had seen under the microscope e.g. cells (a confusion exacerbate by the use of word nucleus in both contexts). There was also confusion about whether particles in solids, liquids and gases were the same size and/or shape, and about whether particles changed size if heated or cooled.
c. *What is in-between particles?* Students were very reluctant to accept the existence of the vacuum in the space between particles, and tended to suggest that this space must be filled with air (usually seen as a continuum). Students knew from previous teaching that "air is everywhere", and were also very uncomfortable with the idea of "nothing". Other justifications given for the existence of air in-between particles included:
   - air is compressible, so it is the presence of air between gas particles which allows gases to be compressed;
   - there must be air in-between water particles because fish live in water and they need air.
d. *What holds particles together?: forces.* Very few students addressed the issue of what holds particles together. If asked for example, why solids should keep their shape, they would at the most suggest that this was because the particles in a solid were tightly packed. A very small number of students acknowledged that *something* must hold the particles in a solid together, and in trying to explain what this might be, talked about energy, magnetic fields, elastic or springs and gravity.
e. *The motion of particles.* As with bonding, very few students addressed issues relating to the motion of particles (even in classes where diffusion demonstrations had been used during the Elicitation lessons). Some students recognised that particles in gases moved, but most felt that particles in liquids would only move if the liquid was poured or shaken and that particles in solids did not move at all.
f. *Macroscopic ideas.* In some classes a few groups produced posters which did not use particulate ideas, but simply re-iterated ideas related to the properties of solids, liquids and gases.

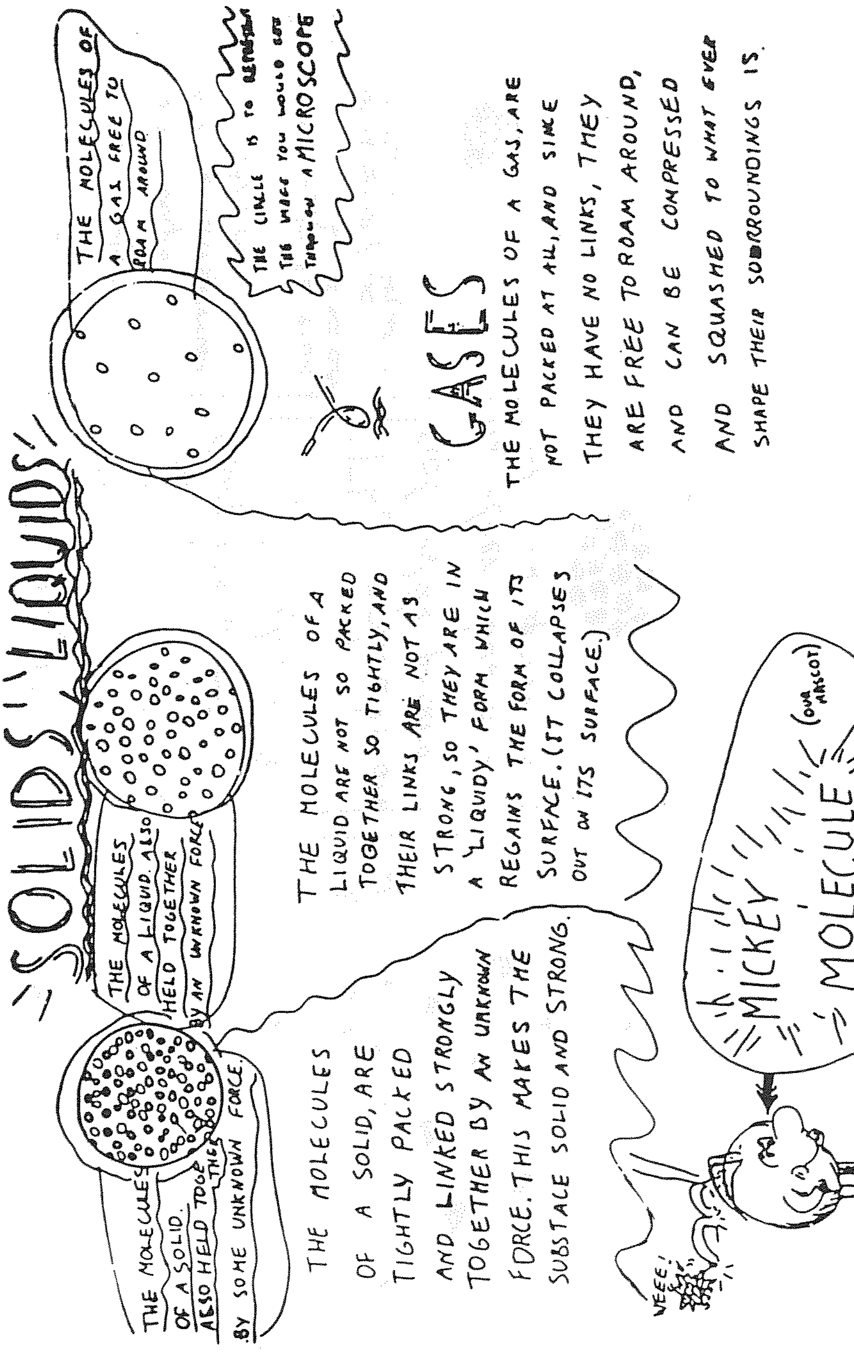
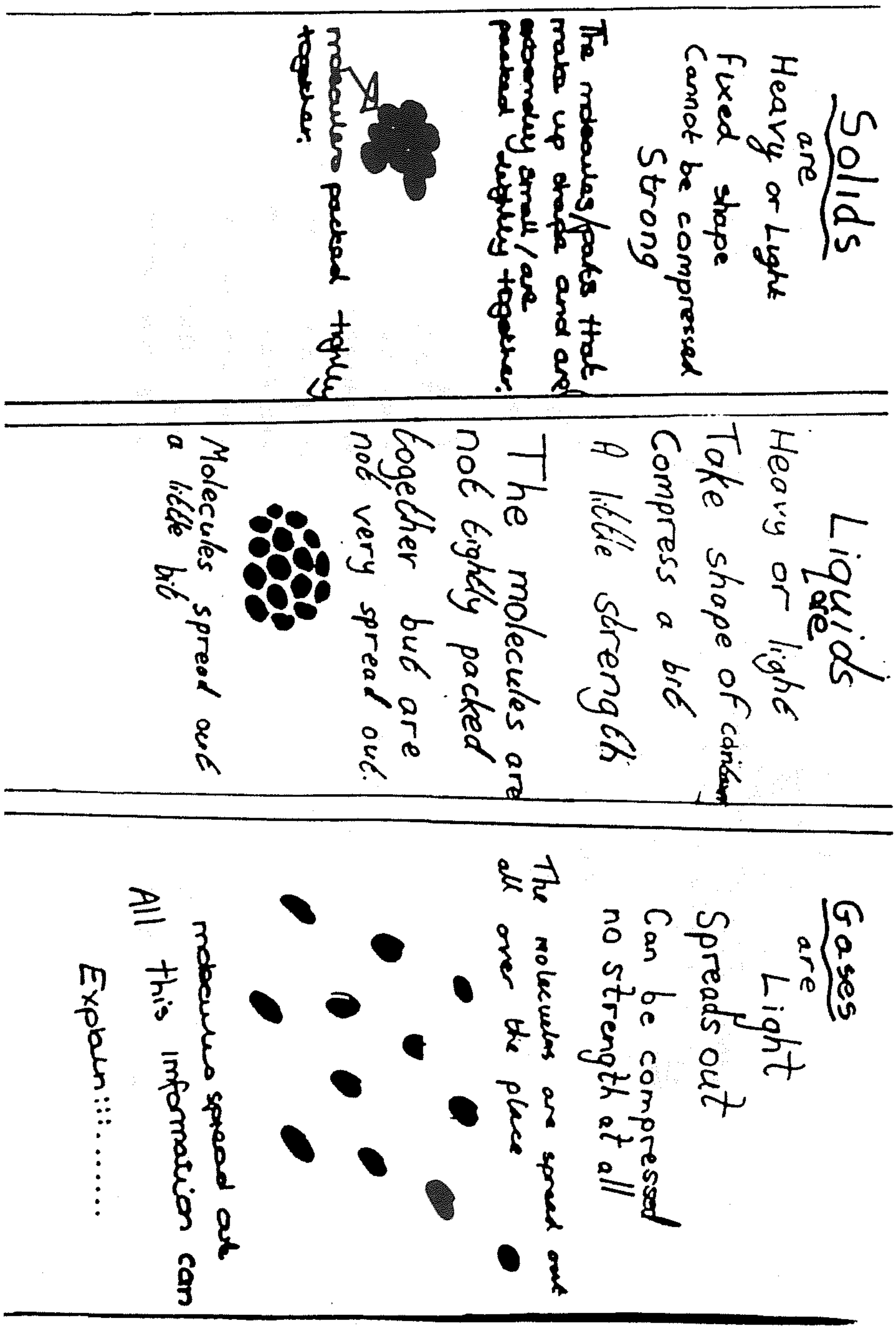
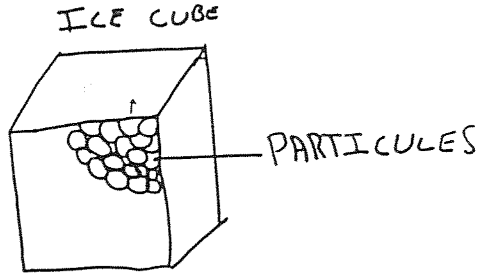


Fig. 3 Posters Produced by Groups: Student Theory Making.

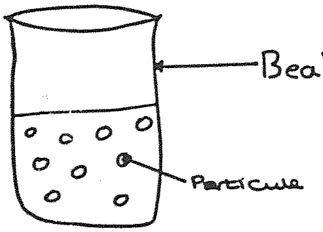

Solids
are
Heavy or Light
Fixed shape
Cannot be compressed
Strong
The molecules/parts that make up shape and are extremely small/are packed tightly together.
molecules packed tightly together.
Liquids
are
Heavy or light
Take shape of container
Compress a bit
A little strength
The molecules are not tightly packed together but are not very spread out.
Molecules spread out a little bit
Gases
are
Light
Spreads out
Can be compressed
no strength at all
The molecules are spread out all over the place
molecules spread out
All this information can
Explain:::.......

SOLIDS:-



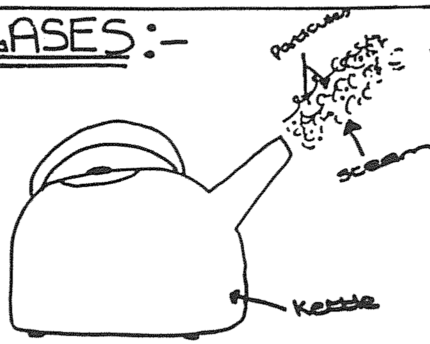
WHEN THE WATER IS FROZEN ALL THE PARTICULES IN THE CUBE JOIN TOGETHER TO FORM A STRONG SOLID BY ALL PARTICUCES LOCKING TOGETHER AND SUPPORTING EACH OTHER

LIQUIDS:-



When the ice cube is melted it turns into a liquid and the particules expand which lets the liquid change shape and size according to the size of the container.

GASES:-



When the liquid is boiled the particules shrink The particules completely seperate and flow around us joining up with the germs around us.

Review, reflection and movement towards the school science view

The outline plan for this section of the scheme was as follows.

- Each group talks briefly about its poster to the rest of the class. At this point the teacher acts as a neutral chairperson, encouraging students to question each other.
- The teacher identifies the gaps between the school science view and students'ideas and introduces activities to try to move students' thinking on.
- The teacher presents the school science view.

In practice, different teachers organised this section of the scheme in quite different ways. Some followed the intended model and worked to the outline described above. Others felt that continuing to allow students to put forward their own ideas was becoming counter productive, and were driven by a desire to make progress towards the school science view. This second group of teachers adopted a more directive approach. Both approaches are now described briefly.

Teachers who followed the outline for this section of the scheme used the initial report back from groups to establish whether there was consensus about some of the ideas which were being put forward, e.g. did the majority of students agree that matter was made of particles? What size where the particles? How were they arranged in solids, liquids and gases? The teacher would then identify any alternative ideas or gaps in students' knowledge about the school science view and address these using practical work, demonstrations, written work and discussion. For example, most students did not recognise that particles have intrinsic motion. The teacher might carry out a number of diffusion demonstrations and ask students to think about how particles in gases and liquids must be behaving in order for these phenomena to occur. In dealing with the question of "what is in-between the particles?" teachers were dealing with student ideas which proved very resistant to challenge. Group discussion and "thought experiments" proved useful in some classes in encouraging students to consider the possibility that there might be nothing in the spaces between particles.

After addressing each issue, the teacher would summarise the consensus ideas of the class, checking at each point that students were comfortable with the ideas being put forward. In this way the school science view was "built up" point by point, with each idea being explored in some detail. When all points had been covered, the teacher would present a final summary and briefly describe the school science view as a "theory" which had been put forward by scientists to explain why matter behaves as it does.

In classes where teachers adopted a more directive approach, this generally took the following form: groups would report back on their posters, then, without any further exploration of students' alternative ideas the teacher would introduce the school science view. This was introduced in a number of ways. The most common approach was for the teacher to thank students for their ideas and to say that s/he was now going to explain to the class what scientists think. In some cases the teacher would point out the similarities between some of the students' ideas and the school science view, but there were few instances in these classes where teachers provided opportunities for discussion of differences between students' ideas and the school science view. In some classes teachers drew more directly on students' posters in presenting the school science view, pulling one "correct" idea from one poster and one from another, but again there was no attempt to explore the alternative ideas put forward on the posters or to consider why these ideas were not acceptable.

The introduction of the school science view in this way, without the provision of opportunities for students to explore their own ideas in relation to the "correct" view, runs counter to the intended aims of the teaching scheme. Why then did a number of teachers decide to take this approach, having worked *with* children's ideas for several lessons previously? Among the factors which seemed to be influencing teachers at this point were the following.

a. *Time constraints.* Many teachers had previously taught the particulate theory of matter in fewer lessons, and by this point in the scheme were beginning to worry about the time being spent on it
b. *Need for closure.* A number of teachers felt (in some cases with some justification) that students were not used to working in such an open ended way and needed the security of knowing the "right answer". By this point in the scheme they felt that it was time to provide students with those answers.
c. *Lack of confidence about working from children's ideas.* A number of teachers had little experience in working in a diagnostic way from children's ideas, and in particular, during the early trials of the scheme, there was little group experience to draw on. For some teachers it was simply much easier to introduce the school science view than to generate a number of teaching strategies to address the wide range of ideas present in their classrooms.

Application of the School Science View

In the final lessons, students were asked to try to use the "theory" or school science view about the nature of matter in a variety of contexts. By now, in most classes, students had a written version of the theory to refer to. All students worked through a series of simple practical activities, similar to those in the Elicitation section of the scheme. In addition some teachers asked students to attempt additional tasks e.g. imaginative writing exercises or small projects.

Some of practical activities were similar or identical to those used in the Elicitations lessons, for example examining sealed syringes containing solids, liquids and gases, melting various materials. Others were different: considering the conduction of heat by a metal, or the expansion of solids and liquids on heating. In considering expansion, students were asked to try out various standard expansion demonstrations for themselves, and to explain their observations in terms of their "particle theory". Most students offered explanations in terms of particles moving further apart or "spreading out".

"The heat caused the rod to expand (the particles were being spread further apart). This is the first stage of a solid melting into a liquid." (Michelle)
"When the rod is heated the atoms vibrate and move around. If they were heated to much they would spread out so much that it would turn into a liquid and then a gas." (Janine)

Many students held on to the notion that particle spacing in liquids was intermediate between that in solids and gases, despite intervention by teachers. Other students attempted to explain expansion in terms of vibration but often struggled to express themselves clearly; for example:

"The vibrations, when heated, become more powerful and so take up more room." (Amanda)
"When a solid is left alone its atoms are vibrating. When heated they vibrate more therefore taking up more room." (Shirley)

Another alternative explanation still offered by a few students was that expansion occurs when solids and gases are heated because the particles themselves expand. In situations such as this it was common for the teacher to explain the school science view to the students concerned.

In general, students responses to the application suggested a readiness on their part to use particulate ideas in attempting to explain various phenomena related to the nature and behaviour of matter. The fact that such ideas are applied with varying degrees of success is to be expected as students will need time and opportunities to try them out and evaluate their usefulness. Some of the questions still being raised by students towards the end of the teaching scheme included the following.
- Why don't particles themselves expand when heated?
- How do gases diffuse through air?
- What are the differences in spaced arrangement between the particles in solids and liquids?

4. CONCLUSIONS

Student and teacher responses to the scheme

Data was collected on students' attitudes to the scheme by use of interviews, open ended writing and questionnaires. Most students appeared to enjoy the scheme and appreciated the opportunity to become actively involved in their own learning. There were many favorable comments about group work. Some more able students expressed initial doubts about certain aspects of the scheme; they expected to be given answers and were not used to being asked for their own ideas. For the most part however, these doubts evaporated as the scheme progressed and these more able students commented that they appreciated being given the opportunity to think in depth about an area of science.

A number of teachers were interviewed during trials of the scheme and all participants also kept a lesson by lesson diary. Most teachers noted that they were impressed by the level of participation of students in group activities, many adding that many students who were not normally motivated in science lessons appeared to be very involved. The major concerns expressed by teachers related to the amount of time needed to allow students to explore their own ideas, and the fact that some teachers felt uncomfortable about allowing students to hold on their own ideas for several lessons without intervention.

Teaching/Learning Strategies for Promoting Conceptual Change

As trials of the scheme progressed it became clear that the restructuring of ideas was not an isolated, one off process which occurred in the middle of a series of lessons, but that it was ongoing, and prompted by a number of different teaching/learning strategies. These include the following:

a. *Elicitation activities*. The elicitation activities had initially been designed to provide teachers with information on students prior ideas. It soon became clear however that students, in the process of putting forward these ideas, were being provided with opportunities for clarification, modification and development of their conceptual understanding. In particular, elicitation activities provided students with opportunities to broaden the range of application of concepts and to differentiate between concepts (Driver, 1989). They also allowed teachers to help students to unpack conceptual problems (Driver, ibid), and to explore some of the underlying conceptual difficulties which they were experiencing.

b. *Generation of student theories*. The "theory making" lesson enabled students to extend and broaden the range of their ideas and to make links between their various ideas about the nature and behaviour of matter. It also gave scope for the comparison of different models (Driver, ibid), either models/theories proposed by different groups and/or the school science view introduced hy the teacher.

c. *Addressing conceptual problems and barriers to change*. Some of the main conceptual problems encountered in the teaching scheme have been described above (section 3). Few of the ideas held by students are open to direct empirical challenge; it is necessary for students to construct for themselves a mental model of particle behaviour in order for example to make sense of simple diffusion demonstrations or brownian motion. Strategies which emerge as having some success in promoting conceptual change all appear to have in common the fact they place students in a situation where they are required to think through a problem in detail. This tended to involve both individual reflection and group discussion of a focused question or task.

d. *Learning by attempting to apply new ideas.* The application activities in the final lessons are much more than a tool for summative evaluation. They allow students to try out new ideas in a tentative and experimental way. Students are explicitly encouraged to use the theory whether or not they are comfortable with it, and to compare their ideas at the end of the scheme with those which they put forward in the elicitation lessons. In such situations further conceptual development can occur, especially where activities encourage students to use ideas in new contexts.

Issues for Further Exploration

Driver (1989) suggests that strategies for promoting conceptual change in science classrooms "need to be investigated in the context of particular domains of knowledge". In the context of students' understandings of the nature and behaviour of matter a clearer picture of conceptual problems is beginning to emerge. There is still a need however for detailed research related to specific conceptual difficulties, with the design, trial and evaluation in classroom setting of teaching/learning strategies which are targeted at clearly identified conceptual problems.

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THE BOUNDS OF CHILDREN'S ATOMISM; AN ATTEMPT TO MAKE CHILDREN BUILD UP A PARTICULATE MODEL OF MATTER

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1. INTRODUCTION

Particulate models are widely used in the material sciences (biology, geology, chemistry, physics) because of their explicative and predictive power in these fields. Despite the fact that since the time of the ancient Greek philosophers, the concept of particle has gone through many theoretical developments, e.g. newtonian mechanics, electromagnetism, statistics, it has retained the property of being invariant under certain transformations.

According to Piaget's work about children's atomism (Piaget, 1968), atomistic conceptions appear in the development of cognitive structures after those of conservation of mass and volume. These results seem to be the starting-point of several curricula. The pedagogical strategies developed in these curricula are based on a view of knowledge-building as a result of individual activity in connection with the physical world. Experimental activities are considered as sufficient for pupils to elaborate particle models, the functions of social interactions remaining in the background.

The results of the evaluation of these curricula have shown that "the experimental activity of pupils doesn't lead them to elaborate particulate models of matter" (Mitchell, 1982), and that numerous pupils attribute observable properties of substances to particles (Novick, 1978; Pfundt, 1981; Meheut, 1982; Brook, 1984; Barboux, 1987). These results led us to discuss the conclusions of Piaget's work about children's atomism. It became clear that the interviewed children proposed explanations of physical phenomena as breaking into small parts (grains, droplets, particles), but that they didn't attribute any invariance to these small parts; the properties of these small parts vary as those of observable systems. This lack of invariance constitutes a fundamental difference between the children's conceptions and scientific atomism.

This discussion leads us back to the foundations of particulate models, to the postulates about invariance which were necessary to their development. We can find this assumption of permanence already in Leucippe's and Democrite's philosophy. This assumption was later discussed in connection with the existence of vacuum, when atomism was renewed, in the seventeenth century. According to the vacuum opponents (Descartes, Lemery...) changes in matter have to be related with changes in the shape of particles; according to the atomists (Bacon, Sennert, Jungius, Gassendi, Newton...), the particles always remain the same and changes have to be related to motion, spatial organization and interactions between particles (Kubbinga, 1983).

2. PEDAGOGICAL STRATEGY

Pedagogical strategies built upon Piagetian works didn't take into account the axiomatic foundations of these models. In this study, we inquired into models that 13-14 year old pupils are able to build upon such foundations. Objects (particles), characterized by invariable properties (shape, dimensions, mass) are proposed as basic material for building models. A sequence of experimental facts has been carefully planned in order to help pupils to develop this axiom. The invariance of particle properties is supposed to lead the pupils to establish relationships between observable changes and variations in the organization and motion of the particles.

So, the tasks submitted to the pupils are in a way syntatic ones: developing initial conjectures consistently with fundamental axioms; these syntatic creations are meaningful because they are proposed by pupils in order to explain observable phenomena. The analysis of relationships between the phenomenological description and the particulate description constitutes another aspect, the semantic one, of tasks submitted to the pupils (Walliser, 1977; Agazzi, 1978).

Experimental field and functions of the model

The sequence of experimental facts has been worked out in order to help pupils to develop the initial axiom (syntatic viewpoint) and to establish the meaning of the parameters and variables thus introduced (semantic viewpoint). So, the interpretation of gaseous state phenomena (compression of a gas, mixing of gases by diffusion) is supposed to lead pupils to introduce variables, viz. distances between particles, and a cause for changes, viz. motion of particles. The interpretation of differences between properties of matter in solid, liquid, and gaseous states is supposed to lead pupils to establish that interparticular distances are shorter in solids and liquids than in gases and to introduce interactions between particles. The interpretation of a change of state (solid-gas) is supposed to lead pupils to get the initial axiom (invariability of particles) significant of invariance of substance and mass in physical changes.

These situations have been selected according to two criteria: a psychological one, viz. the pupils are already familiar with these phenomena, and an epistemological one, viz. these phenomena can be interpreted in the theoretical framework referred to above. Both criteria must be discussed at once.

The pupils are familiar with the chosen phenomena, but is their conceptualization sufficient to be interpreted by a particulate model? For instance, the pupils can have observed expansion processes but still hardly master the differentiation between mass and volume. Can this previous representation of the phenomena hinder the particulate interpretation? Or, on the contrary, can a particulate modelling help make this differentiation easier?

The selected situations are interpretable in the set theoretical framework, but a quick survey shows the bounds of roughly formalized particulate models. Such models make a coherent interpretation of a wide range of phenomena possible, providing that the initial and the final states only are taken into account. The change can then be shown by a change of the pattern and of the motion of particles.

The predictive power of these models remains limited because of the as yet incomplete character of their rules of evolution; nevertheless by making obvious that some evolutions are impossible they allow a reduction of the field of the possible evolutions of a system. Thus the comparison of the size of a diffusing particle with that of interparticulate spaces in a membrane provides a criterion of selectivity of the membrane; that kind of geometrical deduction is currently used to build hyperfiltration systems. On the other hand, with these models, one cannot foresee the evolution of the system, their theoretical content remains as yet inadequate to achieve such a level of prediction. Thus, at a first level, a phenomenon of mixing of two gases can be understood as a change of the spatial distribution of particles, made possible by their motion; the prediction of the evolution of the system requires a more elaborate theoretical framework, including thermodynamic concepts. This applies to many other phenomena particularly the changes of state (solid- liquid- gas). Such models can then appear, in a structuralist theory of explanation (Garcia, 1973; Piaget, 1973) as being descriptive only. If the requirements are less strong, such a theory can be endowed with the quality of "underlying" (Halbwachs, 1973) or stuctural (Delattre, 1979) explanation.

Representation of the model

Pedagogically speaking, one of the motivations for introducing models rests on their power of concrete and perceptible representation of abstract concepts. The survey of French secondary school textbooks shows that their representations of the models are very elaborate and that the complexity of the underlying theories is more than often ignored (Barboux, 1987). At this level of teaching (13-14 year olds) this power of "concretization" has appeared to us as a likely basis from which to evolve a theory. That is the reason why we framed that sequence with the production of iconic representations. This method of representation implies constraints due to its static nature; on the other hand, the pupil is given a great share of initiative in the choice of the significants he uses. One can thus make the variety of the possible representations appear and elicit the pertinent variables of the model by discussing the meaningful or meaningless nature of the different aspects of the representations made by the pupils.

3. METHODOLOGY

Conditions of the experimentation

This is a LIRESPT-INRP joint undertaking. It is actually a research project closely connected with the secondary schooling system because,

- first: of the choice of the members of the research team,
- second: of the selected experimental situations, usual form groups and time table.

This close connection creates some difficulties: time constraints in order to organize and repeat experiments and almost rigid conditions of observation. Yet it allows a pragmatic adjustment of the propositions both to the pupils' cognitive skills and to the usually operating schooling systems.

We held frequent meetings with our teaching colleagues taking part in the experiment, this allowed us to discuss the feasibility of the experiment we were suggesting, and to work out a very precise protocol.

We were able to repeat this experiment in each of two years with about three hundred 13-14 year old third formers, viz. eleven forms distributed in six different schools in the Paris area. It allowed us to take the pupils' first reactions into account, in order to define more accurately the experimental pattern the following year. The tested forms were composed of pupils with several levels of ability so the results are representative of what can be expected from pupils of that age.

The learning took place an hour and a half per week over a six weeks period. This is much longer than the time usually devoted to the first notions on the structure of matter in that year, modelling activities being currently hardly developed.

Data collecting

We defined an accurate protocol with the teachers in order to collect the data obtained during the classes. The data were the pupils' written productions (in every tested form) and tape recordings of the teachers' interventions and of the discussions of several groups of pupils (in three forms).

Prior to the learning sequence we had, by means of written questionnaires, collected data on the pupils' description of the experimental facts referred to. After the sequence we assessed, by means of written questionnaires too, various aspects of the individual model building evolved during the teaching periods.

4. PATTERN OF THE SEQUENCE AND ANALYSIS OF CHILDREN'S PRODUCTIONS

4.1 Interpretation of properties of matter in the gaseous state

Compression of a gas.

A. Characterization of the system and description of the phenomenon. The experimental phenomenon is the compression of a certain amount of coloured gas into a syringe. The teacher carries out the manipulation and moreover he schematizes on the blackboard the piston position at two different times (figure 1).

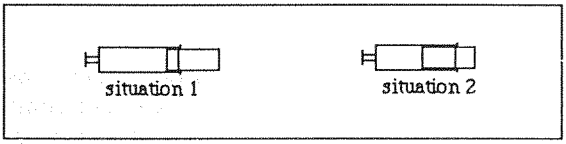


Fig. 1

Each pupil must write down "What has changed, what has not changed, concerning the syringe, and the gas". The way the question is asked aims at a description in terms of change of the state of the quantity of gas contained in the syringe.

Some results.

Mentioned invariants are:	- the quantity of gas	31%
	- its colour	19%
	- its mass	15%
	- its composition	15%
The change is described in terms of:	- compression	60%
	- room occupied	26%
	- volume	17%

In order to describe this phenomenon, the pupils make use of physical concepts such as mass and volume and of qualifying markers such as the composition of the gas, its colour, its degree of compression. Not all of these markers are retained by the teacher, who makes a selection among the properties of the system; the model with a didactic goal cannot of course take every property of the considered system into account. The invariants selected so as to characterize the system are the composition and the mass of gas; the variables descriptive of the change are the volume and degree of compression of the gas.

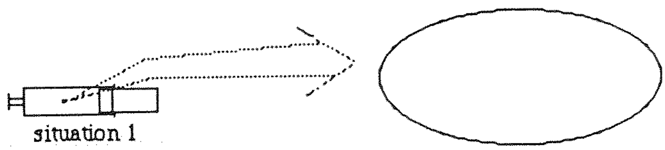
B. Building of a model. The pupils are now required to build, from units (particles) endowed with axiomatic properties of invariance, a model of the previously defined system, and to explain, with the support of this model, the observed phenomenon. Depending on the form groups the pupils must represent two equal mass samples or two equal volume samples of the gas before and after compression.

Equal volume samples. The sameness of the "bubbles" shows the equality of the volumes of the gas samples considered. The increase of density of the gas when compressed must then be shown by the increase of the number of particles in a frame of the same surface.

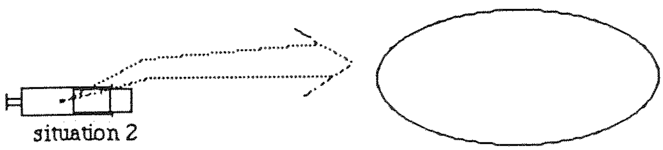
One can represent a gas by particles too small to be visible.
They are ascribed the following properties:

A particle can't cut, can't change shape can't change dimensions

1-Please draw a representation of a very small part of the gas in situation 1.



2-Please draw, for situation 2, a representation of a very small part of gas with the same volume (your drawing must render the observations written on the blackboard).



3-Did you draw the same number of particles in situation 1 and situation 2? Why?

Fig. 2a

Some results. Actually, the majority of pupils (51%) correctly represent a greater number of particles after compression, thus showing the augmentation of the gas density. The justifications are:

- the gas is more compressed 29%
- the particles are closer together 33%.

The connection between these propositions is made quite clear in 12% of the answers. Still quite a number of pupils do represent the same number of particles (39%), some justify that answer by the fact that the quantity has remained unchanged (15%). They reason, in fact, in terms of unchanged quantity of matter, and not in terms of unchanged volume as they were here required to.

Equal mass samples

This is a more complex task. It helps us make sure that the pupils interpret correctly the meaning of the frame they are offered as a representation of the volume of the sample. The increase of the gas density when compressed must then be shown by a diminution of the volume occupied by an equal number of particles (choice of the frame B).

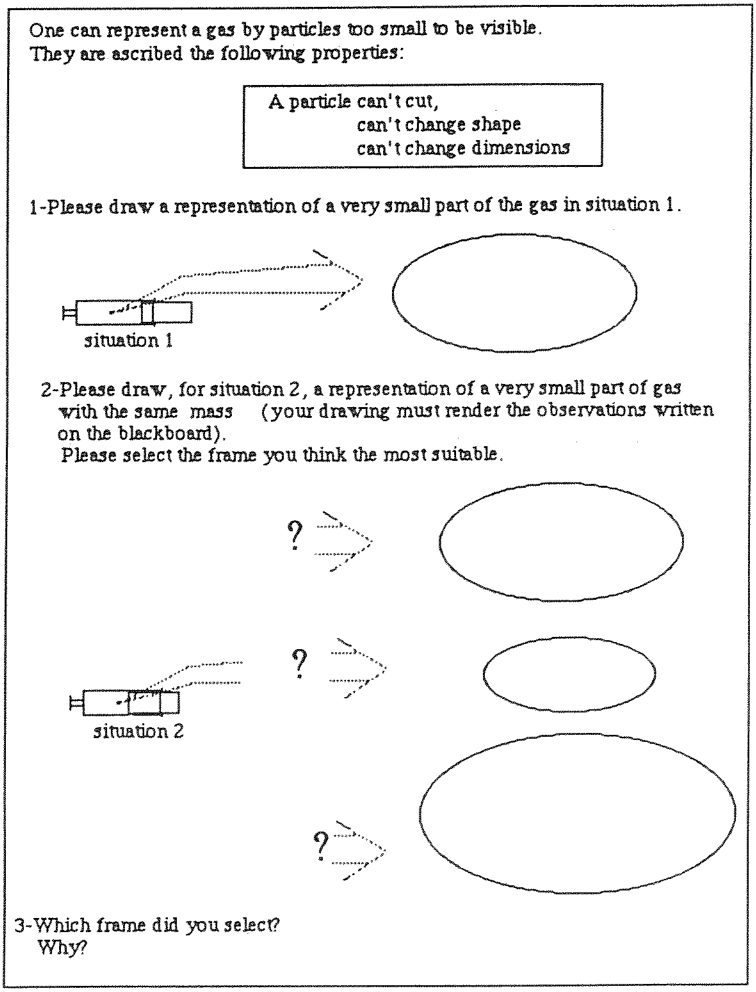
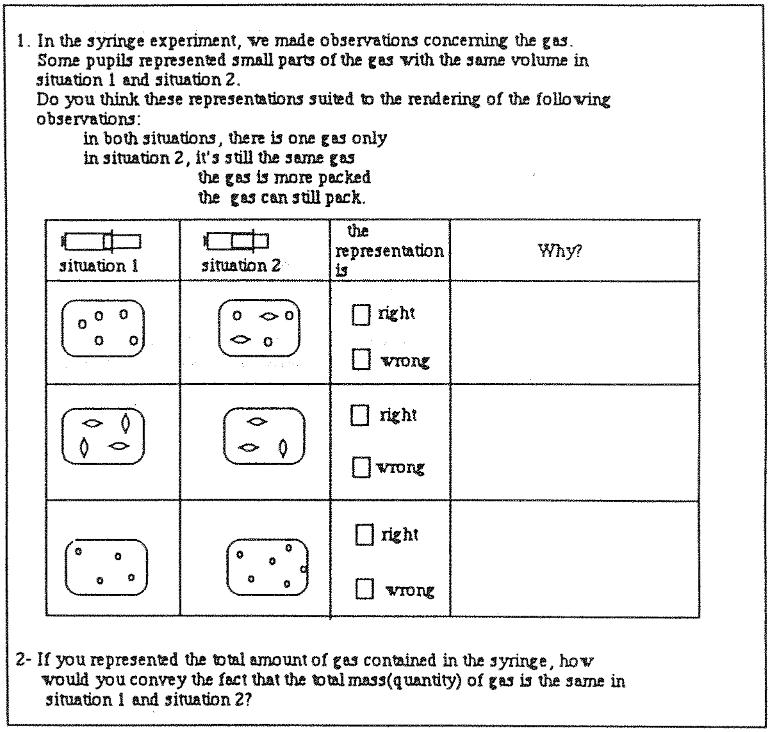


Fig. 2b

Some results. A vast majority of pupils (72%) actually choose frame B, hence showing the diminution of volume of a set mass of gas while undergoing compression. In order to justify their choice, many pupils rely upon the previous description of the phenomenon, namely that the gas is more compressed (29%) and its volume less important (21%). A smaller number can verbalise what they have drawn on paper, viz. particles come closer to one another (12%).

In the majority of representations (56%), the number of particles remains unchanged, which answers the requirement to represent two equal mass samples. Nevertheless about one pupil out of five (21%) wrongly pictures a greater number of particles after compression while choosing a smaller frame. The reasons they give are similar to their friends'. One can only remark that they use the "closer together particles" argument a little more often, and the "same mass" argument a little less often. They seem to have paid less attention to the instruction to represent two equal mass samples and to be more focussed on the rendering of the augmentation of the gas density.

C. Making the rules of correspondence between variables of the model and variables descriptive of the system explicit. The pupils must now discuss in small groups the compatibility of a few representations with the previous description of the phenomenon. Among these representations some have incompatibilities with the description of the phenomenon. Do pupils grasp these incompatibilities? Does this lead them to express clearly the connection between variables of the model and variables descriptive of the modelled system?



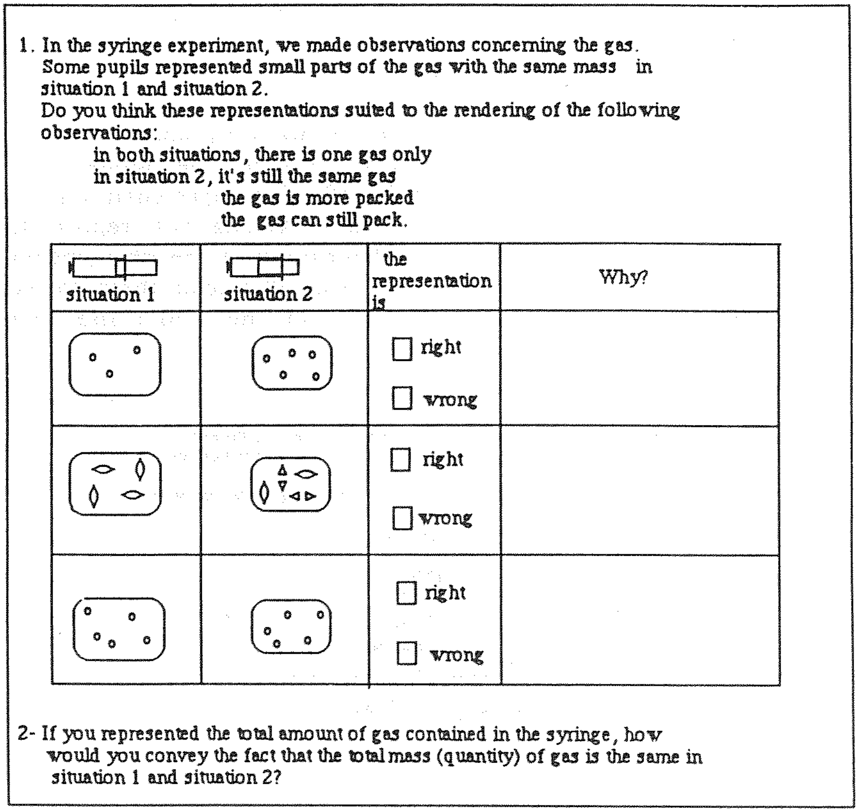
1. In the syringe experiment, we made observations concerning the gas.
Some pupils represented small parts of the gas with the same volume in situation 1 and situation 2.
Do you think these representations suited to the rendering of the following observations:
in both situations, there is one gas only
in situation 2, it's still the same gas
the gas is more packed
the gas can still pack.

situation 1	situation 2	the representation is	Why?
		☐ right ☐ wrong	
		☐ right ☐ wrong	
		☐ right ☐ wrong	

2- If you represented the total amount of gas contained in the syringe, how would you convey the fact that the total mass(quantity) of gas is the same in situation 1 and situation 2?

Fig. 3a

Some results. The representations incompatible with the prior description of the phenomena are properly understood as such by almost every pupil (85 to 98%). In order to justify their rejection, they put forward the number of particles and their shape mainly. A great number of them (40%) argue only at the model level without explicating the relationship between the variables of the model (shape of the particles, number and distrtibution) and the variables descriptive of the system. At this stage of the elaboration of the model we had planned the following connections.



1. In the syringe experiment, we made observations concerning the gas.
Some pupils represented small parts of the gas with the same mass in situation 1 and situation 2.
Do you think these representations suited to the rendering of the following observations:
in both situations, there is one gas only
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the gas can still pack.

situation 1	situation 2	the representation is	Why?
		☐ right ☐ wrong	
		☐ right ☐ wrong	
		☐ right ☐ wrong	

2- If you represented the total amount of gas contained in the syringe, how would you convey the fact that the total mass (quantity) of gas is the same in situation 1 and situation 2?

Fig. 3b

- *The number of particles with the mass of the sample.* In the case of two equal mass samples the number of particles doesn't change; in the case of two equal volume samples the compression shows itself by an augmentation of mass, hence of the number of particles; 8% explicitly establish this correspondence between the number of particles and the quantity of gas: "If the mass is the same, it's impossible to have more particles".
- *The distances between particles and the degree of compression of the gas.* The compression of the gas shows itself by a diminution of the distances between the particles; 9% explicitly relate the number of particles (with a constant volume) to the degree of compression of the gas: "the number of particles decreases when it should increase, the gas is not more packed".
- *The shape of the particles and the composition of the gas.* In the case of a pure gas, the particles are all identical, if the gas remains the same, viz, if it doesn't undergo any chemical transformation, the par-

ticles remain identical to themselves; 8% clearly express this relationship between the shape of the particles and the nature of the gas: "there are two shapes Δ and O and then there are two gases and there must be one only"; among these pupils a few (5%) ascribe a meaning to the initial axiom, through establishing a relationship between the particle invariance and the substance invariance: "the gas particles have changed shape, so it isn't the same gas".

One of the representations under discussion can be interpreted as a splitting of the particles, which is contradictory with the initial axiom. The pupils strongly responded to that contradiction since three pupils out of four point it out: "you must not cut particles"; "one of the rules of particles is that they can't cut".

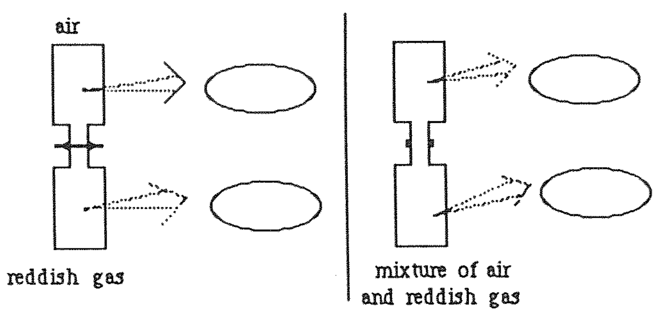
At that point, the pupils were equally asked to give the invariance of the total mass of the air sample contained in the syringe. One pupil out of two renders this invariance of the mass by means of the invariance of the number of particles, 16% further specify that the particles will be closer together.

Attention must be drawn to the fact that one pupil out of four (26%) don't answer the question; they attempt to justify the invariance of the quantity of air empirically, and not to give it by a statement of the model: "the syringe being tightly shut the gas packs because it can't get out. And so the mass remains the same".

Gaseous diffusion

The experimental situation is the diffusion of a coloured gas in the air. These gases have been modelled beforehand. The problem is not only to represent states (separate gases, mixed gases) but also to induce properties of the particles allowing the explanation of the mixing process (fig. 4).

1-Please draw a representation of a very small part of the gas from each flask (equal volume parts). Your representations must render the observations written on the blackboard.



2-Which property must the particles have in order to account for what happened?

Fig. 4

Some results. Two pupils out of three (63%) picture the mixing of gases by a distribution of the particles in the two flasks. The majority answer (39%) to that question is that particles can mix. One pupil out of four (23%) talk of shifting, of mobility of the particles to explain the mixing process. According to some pupils it's only a potentiality of motion without the conditions of realization being specified. According to others, "the particles move while remaining a good distance apart"; "the particles keep moving so that they are uniformly distributed".

4.2 Interpretation of properties of matter in the solid state

The starting point of the modelling of solids is a confrontation of their properties with those of gases. This time the pupils must discuss the validity of the propositions formulated in order to model the gaseous state and suggest consequential modifications so that the model can take into account the properties of matter in the solid state. This worksheet (fig. 5) is filled in separately after small group discussion.

One can represent a solid by particles too small to be visible.
They are ascribed the following properties:

A particle can't cut,
can't change shape
can't change dimensions

Please consider carefully statements 3-4-5 concerning gases; do you think they properly account for the properties of solids. Please write down consequent alterations, if necessary.

	GAS	SOLID
3	Interparticulate spaces are empty.	
4	Interparticulate distances are great.	
5	Particules can move freely and separately. They move and shift desorderly	

Please draw a representation of a very small part of a solid.

Fig. 5

Some results. In order to represent a solid, one pupil out of four (26%) pictures joined particles, a few (11%) leave no interstitial space, which is coherent with their refusal of the existence of vacuum in a solid "There is no empty space, otherwise the solid wouldn't be compact", "Space is not empty otherwise solids could mix". Yet quite a number conserve distances between particles either in the iconic representation (72%) or in the propositions (74%), their main reason being the (low) compressibility of solids.

At this point many pupils introduce dependence relationships between particles. This interdependence gives rise to various formulations, implying a contact between particles: "Particles are welded together", or introducing a medium: "Their is a substance or a force that holds the particles frozen together"; "Their is something, a force that holds the particles like an electromagnetic force". An interparticulate link appears in a few representations (6%): continuous background figuring a substance, lines figuring forces.

At last, according to one pupil out of two (52%) in order to account for the properties of a solid, the particles must be motionless; 10% only consider some sort of motion of particles. This refusal of motion is argumented by several mechanical properties of solids: "Particles don't shift, if they did you couldn't break a pencil"; "If particles shifted and were disordererly, we could with our finger or something else, go through the solid".

One can represent a liquid by particles too small to be visible.
They are ascribed the following properties:

> A particle can't cut,
> can't change shape
> can't change dimensions

Please consider carefully statements 3-4-5 concerning gases; do you think they properly account for the properties of liquids. Please write down consequent alterations, if necessary.

	GAS	LIQUID	SOLID
3	Interparticulate spaces are empty.		Interparticulate spaces are empty.
4	Interparticulate distances are great.		Interparticulate distances are low.
5	Particules can move freely and separately. They move and shift desorderly.		Particules can't move freely and separately. They move without shifting.

Please draw a representation of a very small part of a liquid.

Fig. 6

4.3 Interpretation of properties of matter in the liquid state

The modelling of liquids is realised by means of a confrontation of their properties with those of gases and solids. Pupils must now discuss the validity of the propositions formulated to model the gaseous and the solid states and suggest consequent modifications so that the model can take into account the properties of matter in the liquid state. This worksheet is filled in individually after small group discussion (fig. 6).

Some results. The liquid appears akin to solids concerning the distances between particles (89% do not alter the proposition stated to model a solid). The answers are more divided on the freedom of motion (55% akin to gas- 30% akin to solid) and on the particle motion (43% akin to gas- 30% akin to solid).

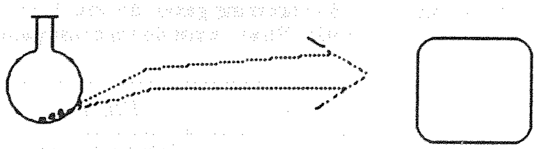
4.4 Interpretation of a change of state (solid-gas)

Depending of the form groups the pupils must represent two equal mass samples or two equal volume samples of iodine before and after sublimation.

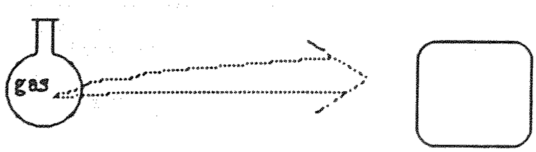
Equal volume samples

The sameness of the "bubbles" shows the equality of the volumes of the solid and gas samples considered. The rarefaction of matter during the sublimation process must then be shown by a diminution of the number of particles for a same surface frame.

1-Please draw a representation of a very small part of iodine in the solid phase.



2-Please draw a representation of iodine with the same volume as previously in the gaseous phase (your drawing must render the observations written on the blackboard).



3-If you represented the total amount of iodine in the solid phase and in the gaseous phase, how would you convey the fact that the total mass (quantity) is the same in both phases?

Fig. 7a

Some results. Quite a majority of pupils (86%) correctly represent the change from the solid state to the gaseous state as a rarefaction of matter (fewer particles in the volume considered). To show that the iodine quantity has remained the same, 39% suggest representing the same number of particles; 37% suggest representing a greater volume for the gas.

Equal mass samples
This task is even more complex (fig.7b). It allows us to make sure that the pupils understand properly the meaning of the proposed frame as a representation of the volume of the sample . The rarefaction of matter must here show itself by an augmentation of the volume occupied by an equal number of particles.

Some results. Quite a majority of the pupils represent the same number of particles (80%) and select the largest frame, thus showing the great variation of volume during the sublimation process.

The answers to these two ways of questioning show that a greater number of pupils are now able to dissociate properly mass and volume.

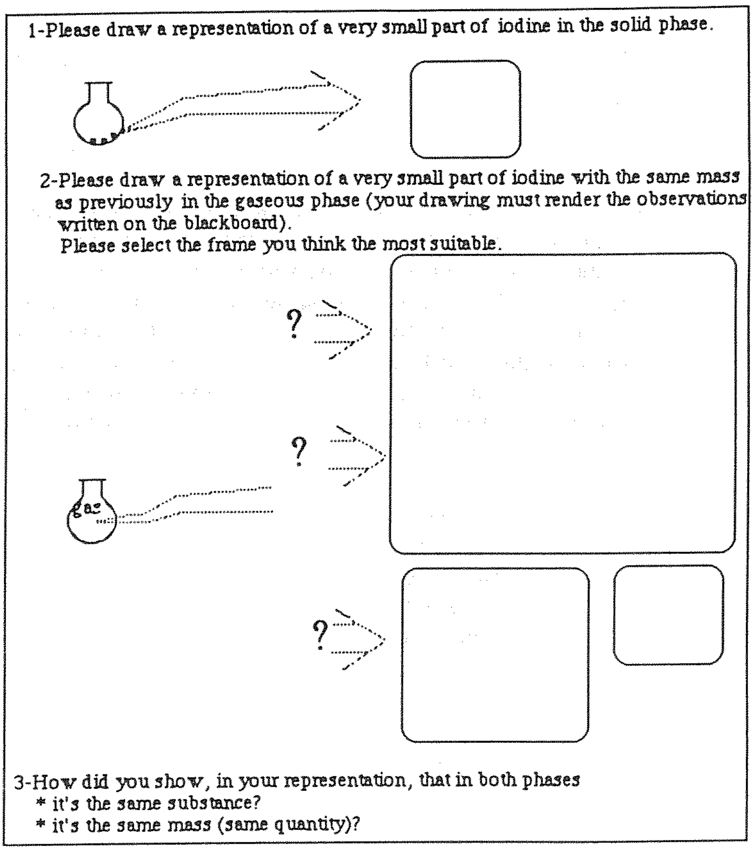


Fig. 7b

5. DISCUSSION AND CONCLUSIONS

The data collected before, during, and after the sequence enable us to discuss the choices we made in order to construct that sequence (see §2).

The analysis of the pupils' productions shows that it is difficult for them to break away from phenomenology and to make the inductions necessary to the development of the initial axiom; only a few pupils prove able to do it. This difficulty of detaching oneself from a sense-based reality is particularly obvious with regard to the existence of vacuum and even more so with regard to the particle motion in solids.

Interparticulate distances, vacuum. The variability of interparticulate distances makes it possible to separate the mass variations from the volume variations. It is put forward by a great number of pupils in order to explain the compression of a gas sample. It's then used again not only as an explanation of the greatest or lesser compressibility of gases, liquids and solids, but of the miscibility of gases and liquids too.

It seems, though, that some pupils were somehow reluctant to conceive an extent devoid of matter. So, in order to model a gas they draw contiguous particles, with no interstitial space, or particles superimposed upon a continuous background. Later on, in order to model a solid they rest upon the properties of cohesion, impenetrability, non miscibility of solids to refuse the existence of such empty spaces.

To what extent did the sequence help to achieve a better dissociation of these two concepts mass and volume? There was a noticeable progression concerning that point during the sequence (see §4.4). Let's compare, moreover, before and after the sequence, the answers to questions relative to the expansion process, a phenomenon that wasn't interpreted during the sequence. There is a noticeable progress in the affirmation of the mass invariance and in the dissociation of the mass and volume concepts. A third of the pupils use a particle argumentation exclusively in order to justify this invariance of mass. A great number of pupils did then prove able to use that aspect of the model in order to interpret a new phenomenon.

Motion. The mobility of particles was introduced so as to explain the mixing by diffusion of two gases. A few pupils propose here a permanent and pluridirectional particle motion, thus taking a considerable leap in the imaginary and drawing a clear line between the phenomenological description and the model. Others simply mention a potentiality of particle motion without specifying the conditions of realization of this motion .

As for solids, quite a number of pupils propose a static model, the properties of solids being considered incompatible with any particle motion. A small number only allow for a local particle motion with no perceptible effect.

Interactions. They appear, in a still hardly elaborated shape, as being explicative of the mechanical proprties of solids, whether contact interactions, or more rarely distance interactions.

The invariance of particles. Resting on historical and psychodidactic data (see introduction), we had chosen to impose invariance as a guide line in the elaboration of the model.

This constraint is generally well respected by the pupils, who prove sensitive to a contradiction (see §4.1). Yet one can remark that, after that sequence, a low percentage of pupils (6%-13%) still misinterpret the augmentation of volume during an expansion process as being a swelling of the particles; 57% interpret it properly as an augmentation of the distances between particles.

In the course of this sequence the pupils used the particle shape as a parameter of the model allowing the modelling of different substances. The answers to the final questionnaires show that a vast majority of pupils (80%) then prove able to establish that meaning.

Further investigations (Barboux, 1987) made us aware on the other hand, that the concept of substance remains, empirically speaking (techniques of separation, criteria of identification), poorly constructed. That is the reason why we asked the pupils to make a prediction relative to a diffusion through a membrane. The prediction the pupils were asked to make deals with one aspect of the membrane selectivity regarding the diffusion process; it rests upon the comparison of the dimensions of the particles of the diffusing substance with the distances between the particles constituting the membrane. This prediction demands that the pupils should take one characteristic of the particles into account: their dimension which up to that point has played no explicative part. During the preceeding sessions the shape difference between particles appeared as interpretative of the difference between substances, but the dimensions of one type of particles were not endowed with any meaning. In order to realize this prediction, about one pupil out of three with the prop of an iconic representation, took this parameter in consideration.

Thus the axiomatic part of the model seems to have been accepted by a vast majority of pupils. The activities proposed in the course of the sequence have made it possible to give a meaning to this parameter of the model, the particle shape. At first a shape difference between particles appeared as signifying a difference between the represented substances. Later on, the particle dimensions appeared as a parameter to be taken into consideration in order to use the model as a prediction tool.

The analysis of pupils' productions shows that the activities of production and discussion of iconic representations have played an important part in these different steps. Nevertheless, this method of representation implies constraints due to its static nature. Using cinetic computer simulations will allow us to go further.

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MAKING SENSE: WHAT USE ARE PARTICLE IDEAS TO CHILDREN?

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1. INTRODUCTION

Research on children's ideas about matter shows that many children have difficulties in appreciating and using the particulate (or kinetic) theory of matter. Many children hold views about the nature of matter in which "particles" have a role, but the properties they ascribe to these "particles" and the ways they deploy "particle" ideas in explaining observed phenomena suggest that their mental models of matter are rather different from the accepted scientific model. Thus "particles" are seen to be able to expand (Piaget and Inhelder, 1974), or to change state (Happs, 1980). Many children have difficulty with the idea that the "particles" are in continuous random motion (Dow, Auld and Wilson, 1978). One particularly difficult aspect of the scientific model is the idea that there is nothing in between the particles; in many children's models, something fills the space (Novick and Nussbaum, 1978, 1981). It is also striking that, when faced with questions which ask them to explain phenomena using (given) particle ideas, many students (at age 15) are unable to do so, and provide explanations wholly in macroscopic terms (Brook, Briggs and Driver, 1983). Furthermore the "alternative" ideas about particles which children hold are tenacious and resistant to change through formal science teaching.

In this paper I want to explore two ideas about teaching the kinetic theory of matter. Firstly I want to suggest that a major reason why the kinetic theory of matter is difficult to teach successfully is that the theory, in the way it is normally taught, is of almost no *use* to children. Their rejection of it can be seen as a perfectly proper response to a piece of inert knowledge. It is, perhaps, important to make clear what I mean here by the word "use". An idea may be useful in the sense of providing a basis for decision-making in everyday situations, or about social issues; or simply in the sense of enabling an improved understanding of natural or man-made phenomena in which the learner has, for whatever reason, an interest. I am suggesting that all too often the kinetic theory is seen by children as of no use to them even in this second, weaker sense.

Secondly, I want to suggest that the sorts of "alternative" versions of the kinetic theory of matter which I outlined in the opening paragraph are better seen not as "misunderstandings", but as necessary steps towards a grasp of the scientific model of matter. This is not simply a question of paying greater attention to children's ideas but of recognising that large and abstract ideas *must* be taught obliquely, through the accumulation of examples and specific instances, rather than by "teaching" the idea directly and expecting that the learner can assimilate it "whole".

2. NAIVE THEORY, CHILDREN'S QUESTIONS AND SCIENTIFIC ANSWERS

I have suggested that particle ideas may fail to take hold in children's minds because they find no use for them. But this is not to imply that children do not have their own questions about matter. All of us spend our lives surrounded by matter and by objects made from differents sorts of "stuff". So it is ha dly surprising that we develop our own ideas and theories about what stuff really is. Hayes (1979) has attempted to sketch the basis of what he terms a "naive theory of matter".

"There are different kinds of *stuff*: iron, water, wood, meat, stone, sand, etc. And these exist in different kinds of *physical state*: solid, liquid, powder, paste, jelly, slime, paper-like, etc. Each kind of stuff has a *usual* state: iron is solid, water is liquid, sand is powder, etc. but this can sometimes be changed. For example, many stuffs will melt if you make them hot enough (which for somethings is *very very* hot, i.e. *in practice* they can't be melted, e.g. sand; and others will *burn* when heated, e.g. wood or flour). Any liquid will freeze if you make it cold enough. Any solid *can* be powdered if you pulverise it with enough effort and determination, etc. There is no obvious standard way of changing a powder into a solid (but wetting it to get a paste, then drying the paste carefully, sometimes works). Some substances, left to themselves, *decompose*, i.e. change slowly into some other (useless) substance; or *mature*, i.e. change slowly into some other (useful) substance. Rusting and wet rot are examples of decomposition, cheese-making an example of maturation ..... (Hayes, 1979: 260; emphases in original).

Hayes mentions only solids and liquids. By implication, another aspect of the "naive theory of matter" is that "gases are not *real* stuff at all". Hayes' sketch of a "naive theory of matter" is a useful starting point, as (in sofar as it is correct) it focusses attention on the sorts of ideas that learners are likely to bring with them to the classroom. It is, of course, a "theory" only in the sense that it classifies and codifies everyday experience. It notes general patterns in behaviour, but does not provide any explanation for them. I suggest that this is an accurate depiction of lay views of matter; we take the properties of the matter we encounter for granted, as given features of our everyday world. Our concern is to be able to predict the behaviour of these types of matter sufficiently well for us to use them to achieve various purposes. We construct for ourselves a *technological* theory, rather than a *scientific* one.

This, in turn, invites us to consider the sorts of questions about matter which children themselves raise. It is difficult to frame the correct questions to ask to elicit these, but a short time spent talking to children about "stuff" suggests that they are curious about why some solids are hard (like steel, or aluminium) whilst others are soft and easily shaped (like putty or plasticene); about why you can see through glass but not through the wall, through water but not through milk; about why this pen is yellow but that ball is red. When thinking about "stuff" they do not raise questions about why smells spread from one place to another; or why balloons go down gradually; or why two liquids when mixed take up a slightly smaller volume than one would expect. This does not mean, of course, that children cannot be *made* curious about these phenomena, or that they do not yield interesting information about the nature of "stuff". But it does mean, surely, that we should feel a little uneasy about a school science "theory of matter" which provides an account of a small-number of phenomena which *we* choose to present, whilst offering no explanation at all of a whole collection of rather more obvious and interesting properties of matter about which children are curious.

If we are to relate our teaching of ideas about matter to children's questions, we immediately face a problem: many children's questions are difficult, if not impossible, to answer using a simple theory of matter. A partial solution to this may lie in the second point made in the introduction: that a theory of matter can be understood only by seeing specific examples of the theory in use, and that learning necessarily proceeds via a series of intermediate steps, or "models", which contain aspects that are, in relation to the scientific model of matter, incorrect. In sections 3 and 4 of this paper, I want to explore this approach in two different ways, firstly by describing some experiences with a major curriculum development project and then using this to suggest some general strategies for introducing and developing particle ideas.

3. CURRICULUM DEVELOPMENT: FROM EVERYDAY CONTEXTS TO SCIENTIFIC CONCEPTS

For the past three years, I have been involved with a team of colleagues and schoolteachers at York in developing a science course for 14 to 16 year old pupils, of a wide ability range, which takes children's everyday experiences as its starting point. It is interesting to look at where and how particle ideas are introduced in this course. The course is called Salters' Science. It follows on from an earlier development, the Salters' Chemistry course, which is now published and in use in schools (Salters' Chemistry, 1987; Hill et al., 1989). The science course is, in the terms currently used in the UK, a dual-award GCSE course. Its name - Salters' Science - comes from its main sponsor, a charitable trust called the Salters' Institute for Industrial Chemistry. The broad principles on which we have tried to develop this course are as follows:

- the topics included in the course should arise from the interests and experiences which are part of the lives of the students, or which they can recognise as being of significance to them in the future;
- from the wide range of topics and issues which meet this criterion, we will select those where *scientific* ideas and concepts can significantly enhance students' understanding;
- this implies that scientific theory is introduced where this is a clear "need to know" it (in the sense of "needing" the idea for improved understanding).

We have a few other practical and methodological criteria, such as a commitment to the use of a wide range of learning activities in class, with an emphasis on active pupil involvement in lessons, doing practical work, taking part in small-group discussions, role-plays, and so on. We also have a majority of practising teachers in the development team, working alongside university based science educators and some industrialists. So Salters' Science might be regarded as a science course with an STS flavour, but which aims to teach science and not merely to teach *about* science. The course is organised as a series of thematic units, with titles like *Clothing, Drinks, Construction Materials, Metals,* and so on (Salters' Science, 1988-9).

The criteria I have outlined above mean, of course, that in developing the Salters' Science course we did not simply introduce the kinetic theory of matter at some point because we considered it an important theory within the scientific framework. Instead, particle ideas come in at the point where we can use them to help students understand better some everyday phenomenon or property or issue. In a thematic, issues- and applications-led course, science concepts are likely to be introduced piece meal, and to be scattered throughout the course. A second phase of the development process is to monitor the extent to which there is sensible progression in the "big ideas" of science, such as energy, and ideas about matter. So where, in the course, are particle ideas in fact introduced, and why? And how are they then developed?

Let me begin to answer those questions by looking at where the students are starting from. We know that almost all children by the age of 12 or 13 have already heard of some particle ideas, either from school science in earlier years or from everyday sources. Words like "atom" and perhaps also "molecule" are in common use. Although students' understanding may be very limited, we can use these terms, and develop the underlying idea that properties and events might be explained by the behaviour of entities which are too small to be seen, in a quite matter of fact way, without explicitly mentioning "The Kinetic Theory of Matter".

This strategy is used in a unit which deals with *Clothing*. Children know that fabrics have different properties. By looking at some fabrics with a hand lens and then under a microscope -- something which many children find fascinating -- they discover that some of the properties can be explained by the structure of the fabric, a structure which is barely visible with the naked eye but is revealed on a slightly lower scale of size. For instance it becomes clear that woollen garments stretch a little because of the loops in the structure. Closely woven cloth like cotton is less stretchy; it is also much stronger than the individual threads it is made from because of the way they are interwoven. The next stage is to look more closely at these threads; again their strength arises because they are spun from individual fibres -- this level of detail can also be seen under the microscope.

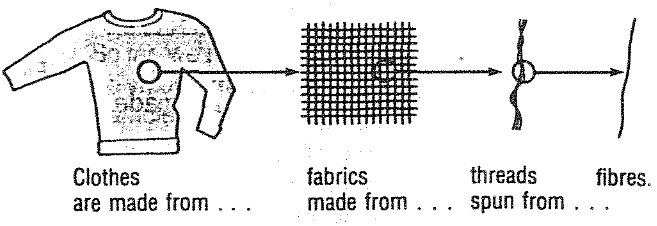

Fig. 1 From the macroscopic to the microscopic level (Hill et al., 1989: 41).

Finally we get to the level of asking about the differences between different fibres themselves. Now we cannot see the "hidden structure", even under the most powerful microscope, but the idea has been implanted that the properties might be explained by the *structure* of the fibre at a level which is too small to see. Fibres are described as made of "long thin particles". If they are lined up closely together, the fibre is strong; otherwise it is weaker. Stretchy fibres have coiled particles, rather like a telephone cord; when pulled, they can stretch out.

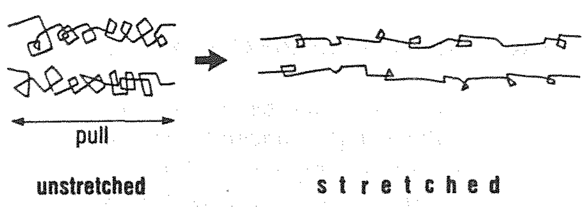

Fig. 2 From the microscopic level to particles (from Hill et al., 1989: 42).

Other properties are also accounted for in similar ways. Fabrics which wet easily are said to have fibres with "water hooks"; nylon which does not wet so easily has fewer. Making coloured fabrics by dyeing them is explained using a picture of dye particles in the water sticking on to the fibre.

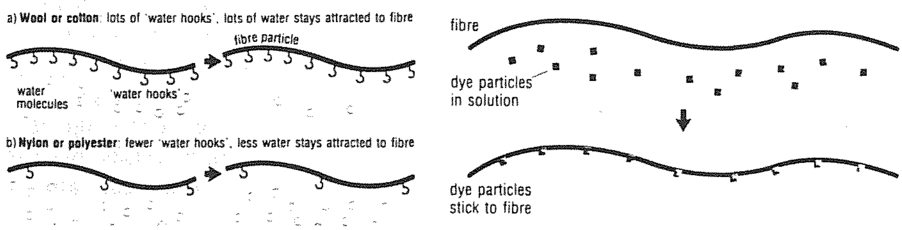

Fig. 3 Wetting and dyeing fabrics -- a particle picture (from Hill et al., 1989, 44, 36).

A similarly pictorial approach is adopted in a unit on *Construction Materials*. In a lesson dealing with the properties of building bricks, the difference between fired and unfired clay is represented in terms of driving water out from between layers of crystals, and forming "strong chemical bonds" to hold layers together. The same idea of weak and strong links is used in the same unit to explain why wood is much harder to split *across* the grain than *along* the grain. Particle level pictures are used to explain the changes which occur when paint dries. Some other units introduce particle ideas in more usual contexts. The *Drinks* unit, for example, discusses dissolving, and looks at the processes involved in making a cup of tea using particle imagery.

These examples are sufficient to give an impression of the approach to particle ideas in the Salters' Science course. The underlying principle is to use (and hence implicitly to sustain) the fundamental notion that the observable, large-scale properties of materials and phenomena might be explained by the behaviour of entities which are too small to see. It relies heavily on simple pictorial images and representations of these invisible entities. This builds up a familiarity with particle explanations before tackling the kinetic theory explicitly as an object of study.

4. INTRODUCING AND DEVELOPING PARTICLE IDEAS

The Salters' Science course has not been specifically designed to introduce particle ideas, unlike "single-concept" schemes of work such as the CLIS unit on teaching about the particulate nature of matter (CLIS, 1987). It is a full 3-year course covering the whole range of science topics; its guiding principles are the rather more general ones outlined earlier. Even so, the way in which particle ideas enter a course which is committed to introducing concepts only where they are useful for explaining may highlight some general issues and strategies involved in teaching these ideas. I want to pick out three in particular.

Getting a "feel" for scale

The fundamental idea which underpins the kinetic theory of matter (and many other scientific explanations) is that observable events and phenomena can be accounted for in terms of the behaviour and properties of entities which are too small to be seen. This is a fundamental paradigm of scientific explanation -- proposing a mechanism on an invisible level. This key idea of *scale* -- of the importance of very small things -- can be introduced gradually. We do not have to go straight from the observable to the atomic/molecular level; there are steps in between. Salters' Science uses clothing fabrics and fibres as a context for this (see Fig.1 above). We need to make greater use of this idea in the early stages of science work, looking at the "grainyness" of many everyday materials and using this to help explain how they behave. For instance, paper is more easily torn than thin cloth, perhaps because of the differences in the ways their fibres are arranged. Going down in scale from the small but visible to the naked eye, to things visible under a low power microscope, we can then get down to the level of invisible causes by exploring the uses of micro-organisms in such everyday contexts as yogurt and bread making. The idea of invisible "atoms" and "molecules" might then make more sense as a *form* of explanation.

Delaying the introduction of ideas known to be difficult

I noted earlier that Hayes' "naive theory" of matter makes no mention of gases. In the Salters' Science course, particle ideas are first introduced to explain the behaviour of solids. I suggest that it may be wise to postpone a consideration of gases until later. Many children need time and experience to appreciate that gases are really matter at all. In addition, research shows that particle ideas about gases are particularly difficult for many children: many have difficulty in understanding what fills the spaces between the particles of the gas, and in accepting the idea of particles in constant random motion with nothing apparently "driving" this motion. If an idea is known to be difficult to teach, we have a choice about what this implies. Either we should give it greater teaching emphasis *or* we should see how far we can get without it. Is the idea necessary at the start, or can it be delayed?

If we introduce particle ideas to explain some properties of solids (and possibly liquids), as the Salters' Science units do, then the next few steps might come from chemistry. Dissolving is an everyday phenomenon which raises questions -- real questions which children can appreciate and often ask for themselves -- about where the dissolved "stuff" has gone, and whether it could be recovered. We can establish, through measurement, the conservation of mass (of matter) in the dissolving process. Dissolving leads naturally on to chemical reactions like the precipitation of a solid when two liquids are mixed. The same question arises: is mass conserved here? Reactions also raise a more basic question about what is actually going on! New and different "stuff" is being produced. How is this possible? How can it be explained? Here particle ideas can provide concrete images of what might be going on at an invisible level.

This sequence might then lead naturally to a way of bringing gases into a theory of "stuff". Is mass still conserved in a reaction where a gas is produced, such as when a "fizzy tablet" dissolves in a glass of water? It is -- provided the gas is collected. So gas is real "stuff" too, with mass.

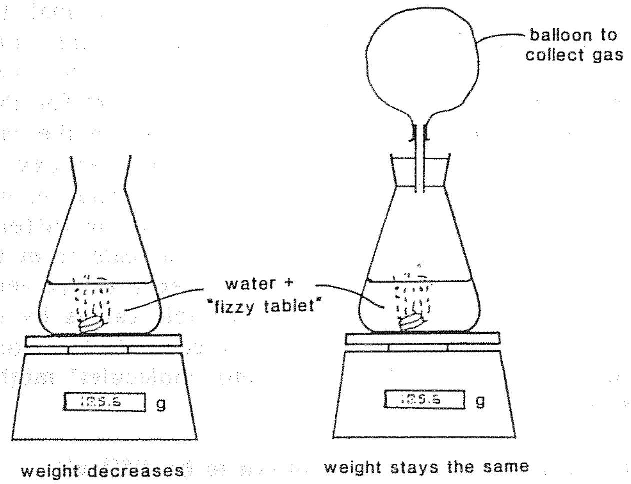

Fig. 5 **Establishing conservation of matter in reactions where a gas is produced.**

It is perhaps worth remembering that the evidence which finally persuaded the scientific community in the 19th century to adopt a particulate view of matter came largely from work of Dalton and others on chemical reactions. We may, in the aspects of kinetic theory we have emphasised, have been unduly influenced by the elegance of the kinetic theory explanation of the gas laws. In fact, for most life-world purposes this explanation adds little or nothing to a phenomenological understanding of gas behaviour. The difficult conceptual problems of continuous random motion and of what fills the spaces between the "particles" can, and I think should, be kept back until a very much later stage in the science curriculum.

Teaching by ostention

The teaching of particle ideas raises an important general issue about how we learn abstract concepts. In an important paper, Kuhn (1977) argues that we learn science concepts by being shown examples of the concept and *not* by being given a set of criteria or "rules" for identifying the concept. This form of teaching is called *ostention* -- "showing". Particle ideas must be taught ostensively, not by providing a set of "rules" about how the invisible particles behave, but by seeing specific examples of the particle theory in use. The reason, as Hayes' "naive theory" correctly implies, is that lay ideas about matter are at the level of generalisations; most people have no idea what sort of thing could possibly count as a "theory of matter". What *kinds* of explanation are possible? Presenting examples of the theory in action is necessary to communicate a sense of what a theory of matter would be, and to allow the learner to see which macroscopic properties they are "allowed" to ascribe to invisible "microscopic" entities.

The emphasis in teaching needs therefore to shift away from evidence for the theory (which is, in the school laboratory, usually less than compelling), and on to *using* particle explanations.

5. CONCLUSIONS: RELATING THE EVERYDAY AND THE SCIENTIFIC

Children come to science classes with a rich background of everyday life-world knowledge about how things behave. If our concern in teaching science is about "science for all" and "public understanding of science" (rather than solely about "the training of future scientists"), then we will need to make a bridge between life-world knowledge and scientific knowledge, for two reasons: to prevent rejection of the scientific ideas in favour of firmly held life-world notions; and to increase pupils' motivation to learn by making difficult science ideas seem more readily applicable and personally valuable.

I began this paper with the suggestion that children may reject the conventional treatment of kinetic theory ideas because they cannot see how these ideas are *useful* to them in explaining their world. But is there any evidence that the approach taken in the Salters' Science course is any more successful? It is too early to have any firm evidence about Salters' Science, but we do have some evidence about students' reactions to the very similar Salters' Chemistry course. A postal questionnaire to 135 schools which presented candidates for the first Salters' Chemistry GCSE examination in June 1988 indicated an average increase of 40% over the previous year's figure in the number of students choosing to continue to A-level chemistry. Increases for males and females were almost exactly the same. Informal feedback from schools and teachers confirms that approaching science from everyday contexts motivates more students to take an active part in science lessons and to continue to study science to a higher level.

6. POSTSCRIPT: THE ROLE OF RESEARCH IN CURRICULUM DEVELOPMENT

The general points I have made about teaching the kinetic theory of matter emerged from a discussion of a science course which tries to start from contexts with which children are familiar, and to introduce scientific ideas as and when they are required to provide better explanations. It is important to recognise that research on children's ideas cannot of itself tell us what we ought to be teaching to children. Research into children's understanding of particle ideas can identify for us the places where children's ideas are most likely to differ from the accepted scientific ones. It can tell us where changing children's conceptions towards the accepted scientific view is likely to be most difficult. It may be able able to describe tested strategies for promoting specific conceptual changes (though I do not think it has yet managed to do this). But it cannot tell us which scientific ideas we *ought* to be attempting to teach. In other words it is about "how" and not about "whether". Aims and objectives must come from other considerations. We need to decide first what we want to attempt to teach to children through school science. And if school science is to be "science for all", then it is not immediately clear that an understanding of the full, unreconstructed kinetic theory of matter should be one of our objectives. Once we know what we want to teach, then research on children's conceptions may be able to help us to teach it more effectively.

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THE NEED FOR A PARTICULATE DESCRIPTION OF MACROSCOPIC ENERGY PHENOMENA

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1. INTRODUCTION

In science, energy has to do with movement and position in a field of force, macroscopically as well as microscopically. It is thus strongly related to work. Energy is conserved and its only forms are kinetic and potential energy. All other forms of energy can be reduced to these forms by considerations at a particle level.

Usually in senior secondary physics education, this scientific energy concept is taken as a final goal. Its teaching starts with the introduction of conservation of mechanical energy in the gravitational field. In situations in which mechanical energy is obviously not conserved, like when a lump of clay hits the ground, the internal movement of particles serves as "an excuse". At the particle level kinetic and potential energy are still conserved. Macroscopically, the 'lost' part of the (mechanical) energy is identified as 'heat', corresponding to a very small increase of temperature.

Quite separate from mechanics, thermodynamics is dealt with afterwards. 'Work' and 'heat' are then used, in a different sense from mechanics, as the energy exchange between systems, caused by the displacement of an external force and by a difference in temperature respectively.

For junior secondary education, it is increasingly widely accepted that energy education has to start from everyday meanings in order to develop gradually towards scientific meanings (Driver, 1989; Duit, 1984; Lijnse, 1982). A thermodynamical approach thus seems to be more suited than a mechanical approach. In the former, macroscopic phenomena are explored, and particle considerations have no important part to play. At the start of senior secondary education, the scientific energy concept described above will thus not yet have been attained (Lijnse, 1986).

In the energy part of the PLON curriculum for senior secondary education at the pre-university level, (Dekker & Van der Valk, 1986) with students aged 16/17, a 'practical' energy concept is taught first, using an extended thermodynamical approach in a 'practice directed' unit 'Energy' (PLON, 1986). It is followed by a mechanical approach in a more 'discipline oriented' unit, called: 'Work and Energy' (PLON, 1985), directed at further scientifically developing the energy concept. In the 'Energy' unit, macroscopic phenomena that are relevant for societal energy issues are dealt with. In some cases, a particle description is used.

Research has been done on the development of students' concepts during instruction with the PLON energy curriculum. An inventory of problems in a first round of research has lead to a thorough revision of the units. The revised curriculum has been subject to a second round of research. In this paper results of both rounds are reported with respect to the merits of a particle model for dealing with macroscopic energy phenomena. As leading questions for this report we take:

- what conceptual problems do students have during instruction with this curriculum, with respect to relating macroscopic energy phenomena to particle descriptions?
- what descriptions with the particle model contribute to a better understanding of macroscopic energy phenomena?

We therefore briefly describe the particle model taught in the 'Energy' unit and ways in which students appear to use it. From this, some conclusions with respect to the revision of the curriculum are drawn. Some experiences with this revised curriculum will also be reported. Finally some concluding remarks are made.

2. THE PARTICLE MODEL IN THE PLON 'ENERGY' UNIT

In the PLON unit 'Energy', the energy concept is taught in relation to energy consumption and production in real technical devices, focussing on efficiency, conservation and degradation. The authors had three educational reasons to include a particle model in the unit.

- *the difference between heat and internal energy*

From the start of the unit, a distinction is made between heat as an 'energy flow' and internal energy in the thermodynamic way. To introduce this distinction, internal energy is described at the particle level, using the transformation of the chemical energy of natural gas into the internal energy of heated water as an example. Accordingly, an increase of temperature is related to particles 'moving faster' and thus having more kinetic energy. After this introduction, the concept of internal energy is used macroscopically, among others in the description of experiments concerning the efficiency of heating devices and a steam engine.

- *work on/by gases and changes in temperature*

For example, the particle model is used to explain why the temperature decreases if steam expands, and why the temperature increases if air is compressed in a bicycle pump.

- *energy consumption and energy conservation*

Energy consumption is reconciled with energy conservation by dealing with degradation as the increasing equipartition of energy among particles.

The particle model used is simple: particles without an internal structure collide with, and attract, each other. The attraction being due to a 'Van der Waals force' that decreases with increasing distance. This model

is already introduced and used qualitatively in the junior years, with respect to processes like heating and melting.
Often being short of time, teachers appeared to spend very little time on the particulate interpretation of degradation. That is why we focus on students' use of the particle model with respect to the other two issues: heat/internal energy and work performed by/on gases.

3. STUDENTS' USE OF THE PARTICLE MODEL DURING THE 'ENERGY' UNIT

Both before and after instruction with the PLON 'Energy' unit, a questionnaire with several items on heating and melting was administered. The students had to use their energy concept in providing reasons for their choices in multiple-choice items. No item explicitly suggested the use of the particle model. During instruction, audiotapes were made of explanations by the teacher in the classroom, and of discussions in three small groups of 3 to 4 students in three different classes. These audiotapes were transcribed and the discussions were analysed with respect to conceptual problems and concept development.

From the answers on an item about heating water in a boiler in the questionnaire, it appeared that it was not clear to many students what happens to the energy supplied in heating. Before instruction 38% thought that energy is used up during the heating, 50% chose the alternative that heat is transformed into the higher temperature, while only 12% chose the alternative in which the energy was attributed to the heated water. The only student that used a particle model in his reasoning, argued that "energy is used up to increase the speed of the molecules".

After instruction, students appeared to have learned that energy is not 'used up'. Now, 70% chose the alternative that energy is transformed into the higher temperature; 30% of the students attributed the energy to the heated water. Only 3 of them (10%) argued along the lines of an increase of energy of the molecules.

This does not mean that most of the students did not know about a particle model. A number of students, even before instruction, felt the need to use a particle model with respect to melting. This appeared from their answers on another item: "when does a piece of wax, being melted, have the most energy?"

The results are shown in the table on the next page. The numbers in brackets indicate the fraction of students that used a particle model in their reasoning.

Accordingly, before instruction 18% of the students used a particle approach. Those who ticked alternative 1 described molecules as being 'active', 'energetic', suggesting that the energy was 'used up' during the melting. Those who chose alternative 2 spoke of molecules moving 'more' or 'faster' after the melting.

Table 1

N=32	before instruction	after instruction
1. during the melting	66% (9%)	21% (6%)
2. when all the wax is melted	16% (9%)	50% (38%)
3. the energy doesn't change	19% (-)	21% (-)

After instruction, the fraction of students giving a particle line of reasoning increased to 44%. Most of the reasoning dealt with 'moving faster', or with 'more molecules having more kinetic energy'. Only one student thought that the kinetic energy does not increase.

From audiotaped discussions we learned that many students had problems in making sense of expressions like 'the internal energy of water' correctly. For example: some of them saw 'internal energy' as the heat supplied. Some others said 'the energy is used up to increase the speed of particles'. Moreover, they had problems in making sense of 'internal transformation' from potential into kinetic energy of molecules, or of external work into change in kinetic energy of the molecules.

In general it became clear that very often students understood the instruction in a way quite different from how the authors and the teachers thought they would. Therefore we decided to thoroughly revise the curriculum in order to build concepts more carefully and gradually. In that way we hoped to avoid misunderstandings, between curriculum/teacher and students, that block the conceptual development.

4. REVISION

Reflecting on the use of the particle model with these results in mind, it became clear to us that in the 'Energy' unit:
- internal energy did not have a clear function until the introduction of the microscopic interpretation of the First Law of Thermodynamics;
- almost no attention was paid to the change of the energy of particles at phase transitions;
- in formulations, macroscopic descriptions were not clearly separated from particle descriptions, so the relations between them remained diffuse;
- a particle representation of kinetic and potential energy was used together with more or less intuitive representations in terms of motion of particles;
- forms of energy transfer ('forms of flowing energy') like heat, external work and electric energy were not clearly distinguished from forms of energy that have to be attributed to objects ('forms of stored energy');
- transformations from one form of 'stored' energy to another (internal

transformations) were not introduced carefully, but more or less presented as self evident.

In the revision we decided to refrain from dealing with the energy concept with respect to the particle model until internal transformations, like kinetic to potential energy, are grasped at the macroscopic level. The simple junior level model of particles vibrating in a grid and moving away from each other at melting, should not be transformed into a model of particles having kinetic and potential energy until that time. Being able to make a systematic distinction between energy sources, energy flows and energy storage, in an 'entity conceptualization' of energy, (Duit, 1984) seems to be a necessary basic structure that needs to be developed first. In the revised 'Energy' unit (called 'Energy Supply', Poorthuis et.al., 1988a), the macroscopic use of this structure is the aim. One of the stored energy forms is internal energy, one of the flow energy forms is heat. Thus, internal energy is only macroscopically attributed to substances. The unit ends with 'the energy equation', which is the First Law of Thermodynamics in its macroscopic form:

the total of energy flow = the change in stored energy;

$$\Sigma E_{flow} = \Delta E_{stored}$$

In the revised 'Work and Energy' unit (Poorthuis et.al. 1988b) this energy equation is elaborated to deal formally with the relations between the various energy forms and thus to internal transformations. After the mechanical concepts of work, kinetic and potential energy are dealt with thoroughly, attention is directed to thermodynamic systems. A model of particles with kinetic and potential energy is then needed to relate work done by/on a gas to a change in temperature of the gas. Internal energy is reinterpreted at the particle level and kinetic and potential energy are related to the macroscopic concepts of temperature and volume/phase respectively. Macroscopic heat and (external) work are related to kinetic and potential energy of particles by the 'energy equation' of a system in the form:

heat + (external) work = change in kinetic and potential energy of the particles

in which heat and (external) work are positive if they are supplied *to* the system.

5. STUDENTS' USE OF THE PARTICLE MODEL IN THE REVISED CURRICULUM

The research has been repeated with respect to the revised material. A comparable questionnaire was administered to 65 students (16-17 years old; 4/5th form of preuniversity education) from 3 schools, before and after instruction and audiotape recordings were made in two small groups.

Heating and change in temperature or phase

In the discussions during the 'Energy Supply' unit, students again and again discussed the question whether heat supply at the melting point leads to rise in temperature.

From audiotaped discussions it appeared that during instruction almost no student felt a need for particle descriptions for the processes of heating and melting. The macroscopic explanation of heat being supplied and internal energy being stored was satisfactory for them. This is also demonstrated by the results of the question on melting described before, that was asked again before and after instruction. The number in brackets again gives the percentage of students giving a particle motivation.

Table 2

N=65	before instruction	after instruction
1. during the melting	32% (2%)	5% (-)
2. when all the wax is melted	41% (8%)	86% (10%)
3. the energy does not change	24% (-)	9% (-)

This also shows that the choice of the correct alternative (2) is higher at the start than in the first round (41% compared to 16%) and so is the increase (45% compared to 34% in the first round).

As to students heat supply is related to a rise of temperature, they intuitively say that the temperature rises if some material is being melted. With the particle model students can find arguments for this:

1. for a particle an increase in speed is needed to jump away from the grid, so the kinetic energy increased;
2. after melting the particles have more 'freedom of movement', more space to move and thus more kinetic energy.

At last all discussions led to the conclusion that there is no temperature rise. However the next time the whole argument had to be repeated, so this particle explanation appears to be very difficult to understand.

Work done by/on gases and change in temperature

In the fourth chapter of the 'Work and Energy' unit, molecular energy of a system is introduced as the total kinetic and potential energy of the molecules. The main problem for students in this chapter is, as it was in the first round, to explain the change in temperature by the work done. The discussions on this subject went into more detail then during the first round. From it, we could trace four incorrect arguments, two of which used a particle model. With hindsight they could also be recognized in the first round.

- *A change in temperature can be caused by heat only.* This appears from the statements of students on adiabatic compression: 'How can the temperature rise if there is only work done?' and: 'I thought there was no temperature rise, no delta E kinetic for there is no heat'. In other words: students did not think of internal energy transformations. This problem continually cropped up for three of the four students of the group. The fourth 'believed' in the First Law of Thermodynamics, so she could give the correct relationship. The other three also wrote down the First Law, but dealt with it as though there was an additional 'Heat Law', relating heat to change exclusively to kinetic energy. At the assessment, two of the three students appeared to have learned the rules for dealing with the First Law and thus had overcome the problem.

- *Temperature rise and macroscopic friction.* As in the first round adiabatic compression was a problem. Because of the direct relation between heat and temperature, an 'internal heat source' has to be found to explain the rise in temperature of the gas. At first, macroscopic friction between piston and cylinder was discussed, leading to the frictionless situation. Then, in the groups, macroscopic friction was replaced by friction between particles. For example, a student argued: "because the distances are becoming smaller, the particles are going to collide more and ... more with each other and that is why they are heated ... therefore heat is liberated". This liberated heat gives rise to the change in temperature. Again, the absence of internal energy transformations appeared to be the core of the problem.

- *Temperature and pressure via increase of the number of collisions.* The student, that 'believed' in the First Law from the beginning, was asked by her group to give a particle explanation of her solution: temperature increases because of the work done. She had to construct a representation for the process herself, as the book does not present one. For this, she (student Si) related temperature to 'colliding faster':

Si: Because you are pumping those things together then they are going to collide faster
El: Friction
Ml: Yes I think so, by friction
Si : Delta E-kin

Si could not distinguish the relevant argument of increase of speed from the irrelevant argument of the number of collisions as she had no representation of how the macroscopic "push" to the piston can lead to that increase of microscopic speed. So the "push" is translated to "increase of pressure", as she elaborated some minutes later: "pressure increases, so the particles are moving faster". In this way she opposed E1 and M1's ideas of microscopic friction.

- *Temperature and volume via 'freedom of movement'.* Dealing with compression, some students related volume to temperature: "But how is that [rise in temperature because of compression] possible if the space in which they have to move is decreasing?" This relation between 'space to move' and temperature, or kinetic energy, also showed up in other discussions. On expansion at phase transition for example: "But if it expands, does it not imply that E-kin increases?"

We already indicated this argument in particle motivations on melting. Arguments on having more "freedom of movement", moving more and the like were given along with "moving faster" and "having more kinetic energy". The former expression offers a chance to the students to relate the supplied heat to rise in temperature.

The relation between temperature and volume is probably favored by the qualitative particle model, used in the junior stage, explaining phase transitions as an increase in motion of the particles.

6. DISCUSSION AND CONCLUSION

In the second round, conceptual problems could be traced in detail. With hindsight, the same problems, though less explicit, were met in the first round. Most problems can, in our opinion, be traced to one basic idea, the 'heat law' as we shall call it. This law states that heat always goes along with change of temperature and vice versa. Somehow, it seems to involve something like a formalisation of the confusion between heat and temperature that is reported in the literature (Brook, Brigss, Bell & Driver, 1984; Erickson & Tiberghien, 1985). It may have, as its basis the idea that all forms of energy can be transformed into "heat", but heat can almost never be transformed back. So, in particular for temperature changes, internal energy transformations from "heat" to another form of energy are hard to grasp. This 'Heat Law', can also be used on a microscopic level relating heat supply to increase of speed or kinetic energy of particles. In that way the idea can be very persistent among most students during instruction with our curriculum.

From this basic idea in adiabatic cases internal heat sources are looked for and found in macroscopic friction and friction between particles. At phase transitions constancy of temperature is often simply ignored. For that students make use of particle arguments relating 'freedom of movement' to increase of speed and kinetic energy.

Because it was not apparent from the first round, this basic idea is not tackled in the revised curriculum from the very start. However, although the revised curriculum did not succeed in solving the problems, it did succeed in explaining them by giving rise to better discussions with less misunderstandings between teacher, curriculum and students.

From these discussions it became apparent, that reasoning by 'heat flow *to*' and 'temperature or internal energy *of*' an object (aimed at in 'Energy Supply') and by the energy equation (aimed at in 'Work and Energy'), is possible and attractive for students. These ways of dealing with heat and energy, however, are not sufficient to overcome the 'heat law', although they help in preventing and clarifying misunderstandings. In the same way, most students did not accept, from the energy equation, that the temperature of a gas can be changed by work. One may argue that the 'entity conceptualisation', used in the 'Energy Supply' unit, favours the idea of the 'Heat Law', i.e. based on the idea of heat being an entity that can be generated and is conserved afterwards. We have experienced, however, that intermediate conceptualisations between real life and the physics energy concept are inevitable and can be used to plan concept development. Of course, crossing over from one intermediate conceptualisation to another gives conceptual problems. However, raised at the right time, these problems can be solved, thus leading to concept development. We have seen that it can work that way with students. We feel, however, that the curriculum should offer still better opportunities for the students to overcome these problems.

In order to do this the following improvements of the units could be made.

- Macroscopic heat has to be distinguished from macroscopic temperature by a microscopic representation of two different effects of heat supply:
  1. increase of speed of the particles related to temperature;
  2. increase of freedom of movement leading to increase in volume and/or phase transitions.
- In addition, some examples of work leading to the same kind of changes like increase of temperature by compression of a gas and by stretching a rubber band, should be experienced by students.
- Macroscopic work by/on a gas has to be linked to temperature by a representation of energy exchange between particles and a macroscopic piston by collisions.

However, introducing a revision like this goes beyond this research, as many other aspects of the existing revised curriculum will first have to be studied in detail.

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CONSIDERING AN ALTERNATIVE APPROACH TO TEACHING RADIOACTIVITY

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1. INTRODUCTION

In current approaches to teaching the topic of radioactivity, explanations in microscopic (nuclear) terms are predominant. In fact, one of the reasons for including the topic in the curriculum is that it is closely related to elementary nuclear physics and thus part of the fundamental scientific core. Another reason is that the topic is a subject of public debate (important applications concern health, energy supply and defence) and is surrounded by controversy (associations with danger). So this topic is also considered important when one's aims are to promote a broad scientific literacy amongst pupils (Eijkelhof & Kortland, 1988). To many science teachers and textbook writers the best possible contribution science education can make towards this scientific literacy is to teach for an understanding of 'how things really work', which means that one has to teach some kind of theoretical explanation. So in the case of radioactivity it is considered self-evident that one should first teach at the nuclear level about what radioactivity actually is, before considering radioactive phenomena and applications (if at all).

This can be seen as an example of a more general tendency in science education which might be called 'the primacy of theory'. It seems quite general to introduce as quickly as possible some kind of theoretical model, often at the particle level. A phenomenological description of natural events certainly may be called 'knowledge about nature', but it is scarcely considered to be real science. It is this standard emphasis in teaching that we want to bring up for discussion in this paper, focussing on the topic of radioactivity.

In section 2 we begin by presenting the general structure of current approaches to teaching the radioactivity topic. These approaches begin with a (simplified) presentation of the basic scientific concepts which play a role in micro-level explanations (atom, nucleus, proton, etc.). These basic scientific concepts are considered necessary for an understanding of radioactive phenomena such as contamination, irradiation and decay. In section 3 we report some of our research findings with two such approaches. It turns out that the basic micro-level concepts are sometimes misunderstood or not understood at all, and most importantly that they play almost no role in pupils' reasoning about issues relating to radioactivity (shielding, remote handling, containment, sterilisation, irradiation of food, Chernobyl). Since we regard these outcomes as unsatisfactory, we present in section 4 some ideas about a different approach. What we suggest is a postponement of the introduction of particle ideas until a coherent macroscopic description has first been developed and can be used by the pupils. Finally, in section 5 we present some lines along which our further research will proceed.

2. STRUCTURE OF CURRENT APPROACHES

A general consensus appears to exist about the strategy for teaching the topic of radioactivity. In fact we do not know of any approach which differs essentially from the following.

1. A nuclear model is presented as an extension of molecular and atomic models:
   - basic scientific concepts such as nucleus, electron, proton, neutron, atomic number, mass number and isotope are introduced.
2. The topic of radioactivity and ionizing radiation is treated in microscopic terms:
   - radioactive process: nucleus → new nucleus + ionizing radiation;
   - nature and properties of radioactive sources: they consist of unstable nuclei; activity is the number of decaying nuclei per second; half-life is the time after which half of the unstable nuclei have decayed;
   - nature and properties of ionizing radiation: α-radiation consists of helium nuclei (2p/2n); ß-radiation consists of electrons; γ-radiation is a form of electromagnetic radiation.

In approaches where everyday life situations involving ionizing radiation are an integral part of the teaching sequence, this is then followed by:

3. A treatment of the effects of ionizing radiation (also starting off with micro-level explanations):
   - ionization, radical formation, damage to cells.
4. A treatment of relevant everyday life situations (background radiation, nuclear energy, radiation in medicine, nuclear arms, use of radiation in industry and agriculture).

We might say that these approaches are built "from above" (Wagenschein, 1962). They start by providing the basic up-to-date scientific concepts which are needed in micro-level explanations (albeit in a simplified form). Introducing these basic ingredients first and relating them to the actual phenomena later seems to be generally considered the appropriate teaching strategy. Science textbook writers and science teachers appear to have become so convinced of the wide and powerful use of the basic scientific concepts that they also consider them fundamental to the learning process.

3. EXPERIENCES WITH CURRENT APPROACHES

By means of pre- and post-tests, interviews, textbook analysis and class observation we studied two current approaches. Both of them have the structure described in section 2 and include everyday life applications (so blocks 3 and 4 can also be identified). We studied a series of lessons based on the PLON unit "Ioniserende Straling" ("Ionizing Radiation"; PLON, 1984; PLON, 1988). This unit is written for 5th form pupils of the higher ability bands. We also studied two series of lessons based on the VNL unit "Straling, je ontkomt er niet aan..." ("Radiation, you can't get away from it..."; Knoester & Lancel, 1988). This unit is intended for 3th form pupils of the middle ability bands.

In the remainder of this section we will describe rather anecdotally some of our research findings with these two approaches. For a more thorough report we refer the reader to Eijkelhof (1990).

The nuclear model as an extension of molecular and atomic models

The VNL unit starts with a chapter called "On atoms", which begins with substances and ends with protons, neutrons and electrons. It can be summarised by figure 1 (which is taken from the unit).

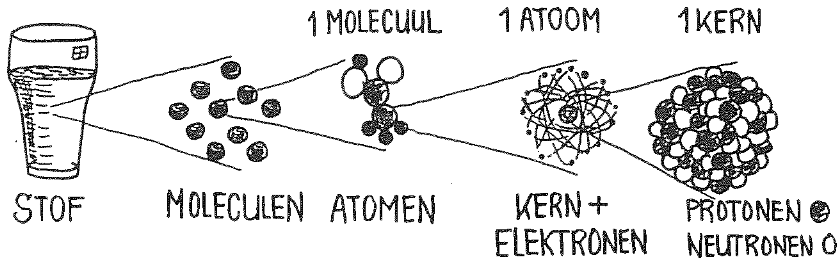

Fig. 1 From substance ("stof") to protons, neutrons and electrons

We found that after two to three lessons with lots of exercises pupils succeeded in remembering micro-'facts' like what the constituents of an atom or a nucleus are and that the atomic number equals the number of protons and electrons.

As reported elsewhere (De Vos, 1985; Nussbaum, 1985), the introduction of microscopic models in terms of a hierarchical structure of matter, rather than as explanatory systems for macroscopic phenomena, leads to pupils taking the models literally, as representations of 'how things really are'. In fact, there really is no other way for pupils to interpret these models at that stage (Redeker, 1982). We might say that the VNL unit develops 'picture-thinking' rather than 'model-thinking'.

A problem with introducing particle models in this way emerged when it was mentioned that the particles cannot be seen. Pupils became very confused and asked questions like: "If they can't be seen, can we then feel them somehow instead?"; "How do we know they exist?"; "How do we know that they look the way they are pictured?". Some pupils commented "So it's all phantasy", or even "So it's all bullshit", and one or two pupils showed they had some imagination themselves and produced their own 'model': "Why say that electrons move around the nucleus? They might as well be moving inside the nucleus".

Some pupils also wondered what molecules, atoms, protons, etc. have got to do with radiation, as the title of the unit is "Radiation, you can't get away from it...". We noted some friction between teacher and pupils during the elaborate treatment of the structure of matter, probably because pupils experienced it as an unnecessary postponement of the topic of radiation, a subject which most pupils claim to be interested in. This elaborate treatment can only be justified by saying that 'later on' they will understand what it was for. As one teacher said: "It is like learning the rules of a game which are very dull in themselves, but once you know them and start to play the game it may be great fun".

Although from a scientific point of view the nuclear model may be considered as basic for an understanding of radioactivity, it certainly was not always experienced that way by the pupils. This is probably connected with the fact that the pupils had almost no experience with microscopic models as explanatory systems for macroscopic phenomena.

A different situation arises for the PLON unit. In the higher grades pupils are already familiar with molecules, atoms and the Bohr model. So the teacher limited the treatment of the hierarchical structure of matter to a short revision and got quickly to the heart of the matter, radiation. As a result pupils did not ask questions like "If it can't be seen, how does one know it exists?" or "What have protons, neutrons and electrons got to do with radiation?".

Micro-level explanations

Again, pupils from the middle ability bands clung to pictorial representations and took the model literally. They now learned that electrons move in a shell around the nucleus as in figure 2.

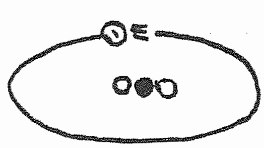

Fig. 2 An electron moves in a shell around the nucleus

When they were then told that some nuclei are unstable and emit radiation, some pupils wondered why this radiation is not stopped by the shell around the nucleus (i.e. the solid line around the nucleus).

As reported elsewhere (De Vos, 1985; Nussbaum, 1985), another result of a premature introduction of particle models is that pupils tend to attribute macroscopic properties to microscopic entities. We found examples of pupils who viewed unstable nuclei as small pieces of radioactive material, for instance when they said that each individual nucleus gradually loses all its radiation or that half-life is the time in which a nucleus loses half of its radiation. We also had the impression that some pupils interpreted the statement that 'something is radioactive (emits radiation) when it contains unstable nuclei', as 'unstable nuclei emit radiation as long as they are unstable'.

However, also instances were found where knowledge of the microscopic facts seemed to be useful to pupils in understanding radioactive phenomena. Given that an unstable nucleus changes when it decays, a pupil was able to deduce that this gives rise to a new substance "because it hasn't got the same number of plus-things [protons] anymore".

Our findings with the PLON unit were rather similar. We again found that pupils sometimes attributed macroscopic properties to microscopic entities. We did not find however that these pupils took pictures literally. In fact, in the PLON unit, the micro-level explanations of radioactive phenomena are treated not so much pictorally as formally. After some exercises pupils seemed able to master the formalism and, for instance, were able to determine X from the reaction equation $^{226}Ra \rightarrow X + {}^{4}He$.

Lifeworld thinking about radioactivity

In an evaluation of the PLON unit (Eijkelhof, 1986), pupils were asked, both before and after the unit, to comment on the risks of some applications of ionizing radiation. It turned out that they used very little scientific knowledge in their reasoning, both before and after the unit. Even before instruction pupils appeared to have some ideas about radioactivity (Riesch and Westphal, 1975) which survived educational intervention. Of course this problem is nowadays well known from the alternative framework literature (Driver, et al., 1985).

By means of pre- and post-tests, interviews and classroom observation we studied pupils' ideas more extensively (Eijkelhof, 1990). That pupils have any ideas at all about radioactivity is not a consequence of direct sensory experience (ionizing radiation cannot be detected by our senses), but must be due to processing information about applications of ionizing radiation. Lijnse, et al. (1990) have indeed found a similarity between pupils' ideas and media reports on Chernobyl. This does not mean, however, that pupils' ideas are just a selected set of facts from these reports. We rather think that their ideas are the result of interpreting the provided information using everyday ways of understanding our surroundings (Redeker, 1982).

A first thing to note is that pupils hold ideas about radioactivity which seem to be shared by lots of pupils from the middle as well as the higher ability bands; in fact we are tempted to say that these ideas also constitute the layman's knowledge of radioactivity. As we try to illustrate below, we think this lifeworld knowledge can best be described by the following three components which strongly support one another. In fact, this mutual interaction establishes a whole which is more than just the sum of its separate components. These components are:

- use of one undifferentiated 'radiation' concept;
- 'conservation' of 'radiation';
- fear of 'radiation'.

Use of one undifferentiated 'radiation' concept

A most striking aspect of pupils' views is the undifferentiated use of words like "radiation", "radioactivity" and "radioactive matter" in any situation which has to do with radioactivity. On the other hand, an aura of danger combined with the presence of something highly penetrating seems to be a signal for situations which have to do with radioactivity. This is why laser light and u.v. light are regularly mentioned by pupils as having to do with radioactivity. We think that in ordinary language words like "radioactivity" and "radiation" are somehow 'contentless'; people have no clear picture of what these are. Most pupils know for instance that 'radiation' cannot be detected by our senses and, when asked whether it can be compared to something else, they most frequently refer to light or heat, of which, from a scientific point of view, their understanding is also rather shaky (Guesne, 1985; Erickson & Tiberghien, 1985). The vagueness, indeterminacy and lack of content of words like "radioactivity" and "radiation" do not seem to matter in ordinary communication (Nagel, 1968; Redeker, 1982): people use them in conversations, read them in media reports and, most importantly, reach an understanding of such conversations and media reports which they themselves experience as sufficient. A possibility of danger caused by something highly penetrating seems to be the context in which these words are understood. This understanding is not so much governed by a theoretical attitude -in everyday life people have no need for deep theoretical explanations- but rather by a pragmatic attitude (Schütz & Luckmann, 1974). Knowing that 'radiation' is dangerous people just want to be sure that sufficient safety measures are taken, but have no need for explanations as to why these safety measures are as they are.

Thus, it seems that in lifeworld thinking only one undifferentiated 'radiation' concept is needed. The public understanding of Chernobyl is a case in point (Eijkelhof & Millar, 1988): the 'radiation' escaped from the reactor, the wind blew the clouds of 'radiation' in our direction, the 'radiation' came down with the rain, by taking in water vegetables got some 'radiation' inside them and people would also get 'radiation' in their bodies by eating those vegetables. When asked where the 'radiation' comes from, many pupils mention nuclear plants or nuclear arms. In the case of natural 'radiation', however, some pupils do not see the need for a source: natural 'radiation' simply surrounds us 'by nature'. Radioactive contamination can also be understood using a single 'radiation' concept. In ordinary language, contamination is often understood as a condition which precedes actual illness. Accordingly, radioactive contamination is understood as a condition which precedes radiation sickness. Indeed, many pupils interpret radioactive contamination as having received (too much) 'radiation'.

The use of just one 'radiation' concept might be related to a common core in lifeworld explanations and predictions proposed by Andersson (1986): the experiential gestalt of causation. Its parts are agent, instrument and object. According to Andersson we experience them as "a whole which is more fundamental than its parts. [...] An agent [...], with the help of an instrument, affects an object". So the 'radiation' (as instrument) affects us (as objects), and in the case of Chernobyl the reactor would be the agent. Also present in the experiential gestalt of causation is the idea that the effects are smaller the further one gets away from the agent. We also found this idea among pupils: at larger distances from the source (for instance Chernobyl) the danger diminishes because the 'radiation' spreads out.

'Conservation' of 'radiation'

A second basic component in lifeworld thinking about radioactivity could be called 'conservation' of 'radiation'. This accounts for the many instances (food irradiation, X-ray photography, Chernobyl) where pupils say that 'radiation' accumulates in living beings, in objects and in a closed space. We put the word "conservation" between quotation-marks, because we do not want to suggest that pupils think 'radiation' remains forever in exactly the same quantity. We merely want to say that many pupils will argue that 'radiation' remains or lingers for at least some time. In fact, many pupils account for a decrease of 'radiation' in terms of a gradual spreading out, although some pupils also mention that 'radiation' breaks down or can be broken down. Some pupils not only mention storage of 'radiation' in an object, but also a subsequent release of 'radiation' by that object. The 'radiation' which was stored in some vegetables after the accident in Chernobyl would for instance have been released by eating them.

We note that the idea of 'conservation' of 'radiation' is strongly related to the use of an undifferentiated 'radiation' concept. What would be the point of the advice not to eat certain fresh vegetables after the accident at Chernobyl, if there was not any 'radiation' inside or on these vegetables? The fact that pupils also use the idea of 'conservation' of 'radiation' in instances of irradiation (food irradiation, X-ray photography) relates to the fact that, in lifeworld thinking, no distinction can be made between irradiation and contamination. Furthermore 'radiation' is strongly associated with harmful effects. In accordance with the experiential gestalt of causation, the instrument must be present as long as the object is affected. Therefore it seems reasonable to assume that 'radiation' must remain in a person for as long as the effects show up -and many pupils know that even after several years effects may show up. The idea of 'conservation' of 'radiation' might also relate to many everyday observations of the way something is absorbed. Storage of 'radiation' in objects and the possible release of 'radiation' by objects come very close to storage of water in a sponge and release of water by squeezing the sponge.

Fear of 'radiation'

Finally, we turn to the third component: the fear of 'radiation', the idea that any situation involving 'radiation' (except perhaps natural 'radiation') is potentially dangerous. In cases in which a personal decision is needed, a feeling of safety is restored by either trusting the safety measures (in the case of someone living nearby a nuclear power plant) or preferring the certain to the uncertain (by deciding not to eat irradiated food; Defesche, 1981).

The strong connection of 'radiation' with fear is continuously reinforced by the media. Almost every report on something 'nuclear' is surrounded by an aura of danger. The fear of 'radiation' also stimulates the use of just one 'radiation' concept and links with the idea of 'conservation' of 'radiation'. To account for the belief that any situation involving 'radiation' is dangerous, the 'radiation' must be seen as present all the time in that situation. If an object has been in contact with 'radiation', the aura of danger makes it likely one will assume that 'radiation' remains present in that object.

In our opinion this complex of three components governs most pupils' thinking about radioactivity before formal education. It accounts for the results of our interview studies and pre-tests. From post-tests, however, we conclude that after current teaching sequences pupils' thinking about radioactivity is still largely governed by the lifeworld knowledge described above. When it comes to using knowledge in everyday life situations, lifeworld knowledge seems to be activated rather than taught scientific knowledge (Solomon, 1983). A major reason for this may be that lifeworld knowledge has proved to be of value to pupils: it often gives them a feeling of having a fair understanding of what is going on. So there is no real need for them to use unfamiliar 'scientific' knowledge. As regards the specific topic of this paper, it is relevant to note that knowledge at the particle level plays almost no role in lifeworld reasoning.

4. SOME IDEAS ABOUT AN ALTERNATIVE APPROACH

In view of the problems we have described with the introduction of microscopic models, trying to account for radioactive phenomena in microscopic terms seems ill-advised, as it may be the first instance pupils encounter microscopic models. However, upper grade pupils from the higher ability bands, who are familiar with microscopic models and from whom one might expect at least some ability for model-thinking, are also found to have hardly changed their lifeworld knowledge about radioactivity after current teaching sequences. Comparing the structure of current approaches with pupils' original lifeworld knowledge, we note a mismatch which results in pupils' inability "to relate the ideas and models of science to things they see happening in their own experience" (Brook, et al., 1988). As Ten Voorde (1977) talks of a premature introduction of moleculular ideas in chemistry education, so we may say that in current approaches to teaching radioactivity the ideas and models of science are prematurely introduced to the pupils, i.e. before they themselves have experienced a need to change their existing knowledge. Inspired by the work of ten Voorde, we suggest an approach in which the attempt is made to evoke such a need by letting pupils experience dissatisfaction with their existing knowledge, for instance by letting them get stuck in their original lifeworld knowledge when they try to describe in their own words the things they observe.

In the remainder of this section we first describe a classroom activity in which pupils may change an aspect of their original lifeworld knowledge. By taking on a new point of view they will be able to overcome an initial failure to express their findings in available language. We refer to Millar, et al. (1990) for a more elaborate outline of a teaching sequence in which pupils, by changing their point of view, develop a coherent description of radioactive phenomena which is entirely in macroscopic terms. To conclude this section, we briefly discuss the extent to which a macroscopic description of this sort prepares the ground for the introduction of micro-level explanations.

Change of point of view

As an example of change of point of view, we present the following experiment aimed at changing the use of one undifferentiated 'radiation' concept:

- take the closed jar with stones in it; hold a Geiger-Müller counter close to the jar and move the counter a few meters away from the jar;
- take the stones out of the jar, pulverise them and blow the dust towards the counter.

A first outcome of the experiment is that close to the jar the count rate is quite high, whilst at a few meters from the (closed) jar the count rate is 'normal'. Because of the fact that close to the jar the count rate is high, the stones are called radioactive. A second outome is that the counter will start counting at a higher rate than normal when the dust is blown towards it. By combining these two outcomes it is found that a description of the experiment in terms of one undifferentiated 'radiation' concept does not work. The experiment suggests a new point of view: the stones emit radiation, which does not reach very far. The second step in the experiment can then also be described in accordance with this new point of view: parts of the stones are able to escape, so even at a relatively large distance radiation can be measured when these parts come close enough to the counter.

We have to stress that since the stones are radioactive the second step in this experiment cannot be carried out in the classroom for safety reasons. We just presented it to make our point clear. The actual classroom activity we propose is that the first step of the above experiment is carried out by the teacher. Instead of the second step, however, the teacher tries by means of an analogy to create what can perhaps be called a cognitive conflict (Stavy & Berkovitz, 1980) or an aporetic situation (Redeker, 1982). The teacher asks the pupils to imagine that the jar is the reactor in Chernobyl and that the place where the counter is standing is the Netherlands. Then the pupils are asked to discuss how, due to the acident, 'radiation' could have been measured in the Netherlands. When pupils say that the 'radiation' could escape because the roof was blown off, the teacher twists the lid off the jar and the pupils may note that the count rate does not increase. When pupils say that the wind blew the 'radiation' in our direction, the teacher blows along the opening of the jar and the pupils may note that the count rate does not increase. In the class observed, pupils were willing to accept this analogy. They came up with various explanations and eventually the 'right' solution arose.

From the activity described above the new point of view that radioactive material emits radiation which does not reach very far may come within reach of the pupils. It also provides them with an experiential context in which they can understand the need for distinct concepts of radioactive material and radiation. This does not mean that they will automatically use the words "radioactive material" and "radiation" in a consistent way or that immediately they will not be able to understand the old 'radiation' concept any more. It does mean, however, that pupils in situations where confusion might arise can solve this confusion by taking on this point of view. A few lessons after the above activity, the question of whether or not radiation is spread by the wind was discussed. A pupil then noted that in a way the answer 'yes' is correct and in a(nother) way the answer 'no' is correct.

This new point of view may also enable pupils to observe new aspects of phenomena, to discover new relations and to word these relations accordingly. Once distinct concepts of radioactive material and radiation are available, one may proceed by focussing on each of these separately. The idea that radiation, once emitted, quickly 'disappears' as such (i.e. cannot be detected anymore), may for instance be developed by noting that irradiated objects near a closed source do not subsequently emit radiation themselves and that by manipulating an irradiated object (for instance cutting it in pieces) no radiation is released.

Micro-level explanations

Ten Voorde (1977) notes that pupils after a time may experience the limitations of simply describing (the relations between) phenomena factually without being able to make predictions. Taking on a theoretical principle as a new point of view may then enable pupils to reason logically about and hence to 'explain' the known phenome ological relations. It seems worthwhile also to try this procedure in the case of radioactivity. However, we have not yet got any experience with such an approach. We wonder for instance whether a coherent macroscopic description of radioactive phenomena necessitates the 'standard' micro-level explanations.

One functional reason for presenting micro-level explanations is that they may satisfy a need to know what the invisible radiation is. They may take away some of the mystery that surrounds it. Another reason is that micro-level explanations may deepen insight into radioactive phenomena. Not just knowing about the phenomena as facts but also knowing explanations may help in 'accepting' the phenomena as they are. Finally we note that micro-level explanations may also enable pupils to make predictions (for instance about decay products).

5. CONCLUSION

Based on our experiences with current approaches and our research on lifeworld reasoning about radioactivity, we propose an approach which starts with the development of a coherent macroscopic description of radioactive phenomena based on pupils' own experiences, rather than with the introduction of micro-level explanations. We think that such a macroscopic description could contribute to pupils' understanding of important aspects of everyday life situations involving ionizing radiation and we can envisage a teaching sequence which stops when this macroscopic description has been attained (Millar et al., 1990). This could be considered for pupils in the lower grades or for pupils with less academic ability. However, for these pupils some micro-level explanations may also be useful. For pupils in higher grades and with higher ability, considerable emphasis on micro-level explanations is unavoidable.

The teaching sequence we are devising for middle ability pupils will be carefully evaluated, in particular with respect to its influence on lifeworld ways of reasoning and to the role and functioning of micro-level explanations after a macroscopic description of radioactive phenomena has been developed by the pupils.

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A MICROSCOPIC MODEL FOR A BETTER UNDERSTANDING OF THE CONCEPTS OF VOLTAGE AND CURRENT

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1. INTRODUCTION

The research reported in this paper is informed by what might be called a constructivist epistemology, because the cognitive approach it adopts builds on the intuitive ideas which pupils already have. Based on previous research we were obliged to revise preliminary versions of a teaching strategy, when these had been tried out in the classroom. The strategy, like other similar strategies (Driver and Oldham, 1985; Hashweh, 1986), pays a great deal of attention to the elicitation and restructuring of pupils' intuitive ideas on certain objects, phenomena or processes, and to their reflections upon the paradoxes thus generated. However, such a strategy does not simply lead to a spontaneous development of science concepts. We felt that there were no concrete proposals about the manner in which the science concepts were to be introduced. We came to the conclusion that in fact there were two stages in the process of conceptualization implicit in the preliminary versions of the strategy: an intuitive stage and an operational stage. The gap between these two stages seemed to be too great to be bridged by the simple device of arranging a confrontation between the pupils' intuitive ideas and the concepts of physics (Licht, 1987). At least two other stages of conceptualization might be necessary: a descriptive stage and a theoretical stage. Inspired by the work of Ten Voorde (1977) we suggest aiming during the descriptive stage at a coherent phenomenological description based on pupils' own experiences with electric circuits. This descriptive stage would serve as a link between the intuitive and the operational stage. The theoretical stage is required at the moment when the operational relationships are not intelligible, plausible and fruitful enough for pupils to change some of their most persistent intuitive ideas about electricity. Model-thinking should be postponed to the theoretical stage until sufficient phenomena are described.

However, we argue that for a proper understanding of a topic not only operational relationships are necessary but also explanations of these relationships in terms of processes which deal with changes of variables. Micro-level explanations may deepen the insight into these changes of variables at the macro-level. They also enable pupils to predict new relationships and changes.

In figure 1 we present a rather broad description of the planned stages of concept development and some of the characteristics of each stage.

Stages	**During this stage the pupil should arrive at statements about ....**
Intuitive stage	..... objects, phenomena or processes on the basis of certain intuitions, preconceptions or idiosyncrasies of usage in mother-tongue discourse. During this stage, reliance upon contextual clues and personal experience is still making itself felt.
Descriptive stage	..... regularities in objects, phenomena or processes on the basis of direct empirical observations of (causal) relationships between qualitative or semi-quantitative properties.
Operational stage	..... explanations of the regularities found during the descriptive stage, on the basis of empirical measurement of relationships between quantified parameters defined by algebraic expressions. A qualitative analysis of the functional relationships among variables is also included.
Theoretical stage	..... explanations of the relationships found during the operational stage. During the theoretical stage the relationships between the concepts concerned can be incorporated into a consistent model. The change of a variable can thus be explained in terms of the model. Macro-micro relationships, which tie macroscopic parameters with microscopic concepts, rules and models are also included.

Fig. 1 A general description of the four planned stages in an educational process aiming at concept development.

To present this description of the planned stages in a less abstract way we give a brief outline of these stages for the topic of electric circuits. Although the research reported on in this paper mainly deals with the intuitive and the operational stage, we think that for a better understanding of the research findings it is necessary to present the broader context of our ideas and hypotheses on the planning of concept development in the domain of electricity.

2. THE PLANNED STAGES FOR CONCEPT DEVELOPMENT IN ELECTRICITY

The possible content of pupils' statements during the intuitive stage is obtained from available research data. As regards the area of electric circuits the following alternative conceptions in answering qualitative questions have been noted in previous studies (McDermott & Van Zee, 1985; Shipstone, 1985; Cohen et al., 1983; Kuiper et al., 1985).

a. Many pupils seem to believe that the same amount of current is supplied by a battery independent of the circuit connected, and that the current is 'used up' when it flows through a bulb.
b. Instead of reasoning that all parts of a circuit are interrelate and influence one another, many pupils think that a change in a circuit has only local or sequential ('downstream') consequences.
c. Pupils tend to be current minded rather than voltage minded, confusing cause and effect.
d. Most pupils insufficiently discriminate between related concepts such as current, voltage, energy and power.

The ideas of these pupils are important and need to be dealt with during the intuitive stage of the educational process.

During the descriptive stage, it seems possible to avoid some of the conceptual difficulties mentioned above by choosing the energy concept as an entrance for electricity education. The energy concept is more closely related to the direct observations of pupils with respect to the relative brightness of bulbs or the relative speed of electric motors than the concepts of voltage and current. These concepts, on which most of the studies report, can now be postponed to the operational stage as concepts which have the power to explain the regularities observed during the descriptive stage.

We use the following symbols to present some of the possible pupils' statements during the descriptive stage: N_p = the number of energy producers; N_c = the number of energy consumers; E_p = the total amount of produced energy in a certain time; E_c = the total amount of consumed energy in a certain time; and the extra indices s and p are for series and parallel connected components respectively. The following qualitative or semi-quantitative statements can be made from direct observations during the descriptive stage:

a. if $N_{p,s}$ increases then E_c increases and so does E_p;
b. if $N_{p,p}$ increases then E_c remains the same, although energy is available a longer period and so E_p remains the same;
c. if $N_{c,p}$ increases then E_c increases and so does E_p;
d. if $N_{c,s}$ increases then E_c increases and so does E_p;
e. if a circuit is interrupted then E_c=0 and so E_p=0;
f. due to a short circuit E_c=0 in the components but E_p is big.

It seems possible that pupils could arrive at these statements based on direct observation of changes in components such as bulbs, electric motors and batteries. They can even apply the discovered regularities in other contexts, such as the use of electrical energy in the household.

In our view, teaching materials which fit into this descriptive stage are especially suitable for the lower forms of secondary education. At the moment, our group at the Free University is developing curriculum matecircuits the following alternative conceptions in answering qualitative questions have been noted in previous studies (McDermott & Van Zee, 1985; Shipstone, 1985; Cohen et al., 1983; Kuiper et al., 1985).

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In our view, teaching materials which fit into this descriptive stage are especially suitable for the lower forms of secondary education. At the moment, our group at the Free University is developing curriculum materials in which we try to guide most of the pupils from the intuitive stage, via the descriptive stage, to the operational stage.

During the operational stage, the pupils should come to statements in terms of voltage, current, electrical energy, power and resistance by empirical work during practicals and teacher demonstrations. Put in algebraic expressions, we can summarize the statements in this way: $P = V I$; $I = V/R$ and $E = P t$. This conventional quantitative analysis of an electric circuit deals with well defined algorithms, and can thus be applied to a variety of circuits. But bearing in mind the statements during the descriptive stage, the relationships during the operational stage should play a different role compared to their traditional role in teaching electricity. Traditionally, at least in the Netherlands, the pupils are expected to explain observations directly in terms of voltage and current. In the approach suggested here, it should be clear to the pupils that the relationships during the operational stage have explanatory power for the regularities discovered earlier during the descriptive stage. However, during the operational stage pupils should also reason in terms of functional relationships.

During the theoretical stage, the statements consist of macro-micro relationships which involve the association of phenomena with processes. The underlying processes of the operational relationships are now described in terms of motions of charged particles, forces, fields and potentials (in their microscopic sense). In this way, the concepts studied in electrostatics can be integrated in the analysis of electric circuits. Although we have to be aware of the fact that even experts do not carry out such an analysis routinely (Heald, 1984), it seems important for a pupil to be able to understand, for instance, the process through which increasing the source voltage will increase the current in a circuit. It is clear that knowing how to deal with quantitative and functional relationships during the operational stage is sufficient to solve most of the conventional problems.

It is our *hypothesis* that pupils who are able to operate with macro-micro relationships will have fewer difficulties with the concepts dealt with during the operational stage. In the rest of this paper we try to portray the research findings as evidence for this hypothesis.

The question is how to present to pupils some macro-micro relationships already during the operational stage in an intelligent, plausible and fruitful way, without negative interference during the time the full scope of these relationships is on the agenda during the theoretical stage.

3. A MICROSCOPIC MODEL

We would like to make a case for seeking a mode of model-building which provides students with explanatory tools they can use in their explanations of the regularities found during the operational stage. Therefore, we have generated a subatomic model of electron flows and electron densities which enjoys explanatory power during the operational stage. Our expectation that such a model can be useful and productive in educational terms, is supported by recent research as well as by classroom experience (Kircher et. al., 1975; Black et. al., 1987; Licht, 1989).

The model is based on the idea of differences in charge densities (concentrations) in separate parts of a circuit. From a physics point of view these differences are very small compared to the number of charges which contribute to the electric current; the charge densities also should be located at the surface of the components with resistance. An electric field in a resistor is then caused by a gradient in the charge density located on the surface of the resistor. The physicist attributes electric energy to an electron due to an electron density in its vicinity: the higher the electron density, the higher the amount of electric energy.

Unfortunately, very little is known about pupils' concepts of the actual microscopic mechanisms and their interpretations in terms of electrostatic entities. As far as we know, only Eylon and Ganiel, after an analysis of student responses to a questionnaire and an interview, report on this issue in the following way: "What emerges from this analysis is the realization that pupils are not able to tie concepts from electrostatics into their description of phenomena occurring in electric circuits. This leads to a number of difficulties. First, the concept of voltage remains vague; its formal definitions (quoted correctly) are not utilized operationally. Secondly, most pupils do not create a consistent picture of the mechanisms, and are therefore unable to explain phenomena. We note in passing that this situation does not necessarily represent misconceptions, but rather the lack of any clear concept. Thirdly, we believe that this absence of a macro-micro link impedes pupils' ability to conceptualize the electric circuit as a system and to appreciate the functional relationships between its parts" (Eylon & Ganiel, 1990).

We have chosen for a microscopic model which, on the one hand, can serve as an attractive alternative to the intuitive ideas mentioned above and, on the other hand, can be used as a basis for a more complete theoretical model in a later stage of the educational process. Our model is represented in drawings in the textbook (fig. 2) and in a simulation programme on a Personal Computer (MS-DOS machine). This programme offers pupils the opportunity to build a circuit with batteries, bulbs and resistors. They can ask the computer to give the values of current and voltage for every component in the circuit, as well as for the voltage between two arbitrary points in the circuit. In this way, the programme helps the pupils to explain the relative brightness of bulbs in terms of voltages and currents. Pupils for whom this explanation is not effective may choose a microscopic representation of current and voltage. The current is represented by moving dots (electrons) on the screen, and the voltage by differences in dot densities (electron densities) between two areas in the circuit separated from one another by a battery, a bulb or a resistor. The model presented in this way has the potential power to promote conceptual change with respect to the intuitive ideas mentioned above, for instance:

a. The idea of current consumption comes under pressure when a pupil counts the number of electrons (dots) passing on both sides of a bulb.
b. The model promotes a way of reasoning in which only the voltage across the battery is a given and constant entity. After all, the difference in electron density between the two poles of the battery is always constant.
c. Local and sequential ways of reasoning are less attractive because in this model a change somewhere in the circuit does cause changes in all the electron densities which are not directly linked to the poles of the battery.
d. By giving a more concrete representation of current and voltage, and with the addition that an electron has more energy as part of a high electron density than as part of a low electron density, it can be expected that pupils come to a better discrimination between voltage, current and energy.

It is clear that we have selected some aspects of a much broader microscopic model which can be dealt with during the theoretical stage. For instance, during the operational stage we do not speak in terms of forces, fields or potentials. We just introduce a way of representation of the three target concepts voltage, current and, more implicitly, energy in which the dynamic characteristics of electrons play an important role.

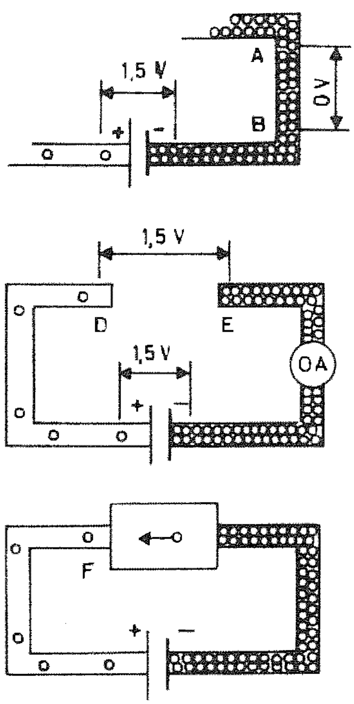

Fig. 2

4. SAMPLE, TEST TOOL AND THE DESCRIPTION OF THE INSTRUCTIONAL MATERIALS

Sample and test tool

The research data presented in this paper were gathered from 75 fourth-form pupils (average age 16 years) in a secondary school. These pupils already had followed at least 35 teaching hours on electricity in the second and/or the third form. In the fourth form, the basic knowledge of the concepts current, voltage, electrical energy and power has to be expanded and connected to other concepts and other topics in physics. We therefore use a multiple choice test in lesson two on electricity in the fourth form as a diagnostic entrance test during the intuitive stage of the teaching strategy. The test tells us how the pupils interpret several problem situations in a qualitative way in so-called simple electric circuits. The test consists of 18 questions which are modifications of items used by Closset (1984), Shipstone (1985) and Shipstone et.al. (1988). It is possible to construct four different reliable scales from clusters of items related to the idea of current consumption (code CC), the idea of the battery as a constant supply of current (code CS), local and sequential ways of reasoning (code LS) and a mistake in or a lack of discrimination between current and voltage (code CV) respectively (Licht & Thijs, 1989). All students who score more than 30% on a specific scale are directed to a related remedial learning programme that takes about one 50 minute lesson. Each remedial programme tries to confront the pupils' intuitive ideas directly with the concepts of physics as they are to be dealt with during the operational stage, without spending any time on possible regularities found during the descriptive stage. This is because the pupils are already encountering this topic for the second or sometimes even the third time. The computer simulation on macro-micro relationships is part of remedial programme 4, linked to the cluster of items on the discrimination between current and voltage. The diagnostic test and the four remedial programmes are part of a chapter of a complete physics textbook for the higher forms of secondary education. They are therefore not only constructed for the purpose of this research.

After the remedial teaching period the diagnostic test is applied for the second time just for research purposes. We thus gained some insight into the extent to which the pupils' own intuitive ideas have been challenged during this period of remedial teaching.

After this remedial period of two or three lessons, the teacher presents the simulation programme to the whole class. One week after this demonstration and discussion session we used the diagnostic test for the third time again just for research reasons. In this way there are three occasions on which research data are gathered:

occasion 1: in lesson 2, just before the remedial period;
occasion 2: in lesson 5, just after the remedial period;
occasion 3: in lesson 8, one week after the classroom demonstration of the computer simulation.

A description of the instructional materials

Before we present the results we would like to give an impression of the general structure and character of the four remedial learning programmes. Each remedial programme takes about one lesson and is constructed along the following lines.

a. Each programme starts with two or three multiple choice questions, just to see if the answers still correspond to the answers in the diagnostic test with 18 questions. If the answers are now all correct, we point out that this result is surprising because this was not the case during the diagnostic test. The pupil may now choose either to proceed or to stop with the remedial programme. In practice, this situation hardly ever occurs because pupils give comparable answers to those in the diagnostic test.

b. What follows then is a text which culminates in the following sentence: "It looks as if you reason in the following way ......". Here we try to convince pupils that their way of reasoning is not strange or non-scientific. We present situations involving rivers and waterfalls to which their way of reasoning is suited very well. But we also emphasize that the situation in electric circuits is quite different and that it is not possible to use these particular ways of reasoning. Physics tells us something different.

c. The reading sections mentioned in a. and b. are followed by a practical element in which the pupils build the circuits themselves from the schemes already presented in the questions of reading section a. With respect to remedial programme number 4, which deals with the discrimination between voltage and current, the practical element consists of the computer simulation programme. The scope of this programme has already been described. At all times, students must make their expectations explicit, both on paper and in discussions within the small group of three or four pupils who are doing the same remedial programme.

d. In the last section, pupils have to write their own summary and compare it both with the summary of the other group members and with the summary given on the last page of the chapter.

5. LEARNING EFFECTS IN TERMS OF TEST RESULTS

Results on the diagnostic test

We present here the data of the total group (N=75) on all three test occasions, making no distinctions between pupils who actually were referred to a certain remedial programme and those who were not. Thus the figures give us a global impression of the effects of the different remedial programmes. More in depth studies are necessary to come to better founded conclusions. However, we can come to some preliminary conclusions using the results presented in figure 3.

Scale Description	Scale Code	Related Remedial Programme	Mean % on occasion 1	2	3
Current Consumption	CC	1	25	15	2
Constant Supply	CS	2	53	37	17
Local/Sequential	LS	3	34	17	5
Current/Voltage	CV	4	62	21	14

Fig. 3 Mean percentage scores on the four scales on three test occasions (N =75).

When considering the testresults on the first occasion, we should remember that the pupils already had studied electricity fairly intensively during their school careers. Many of them were nevertheless diagnosed as requiring two or three hours of remedial learning. The short term effects, that is, the improvements in testresults shown on the second occasion, were considerable and support our view that it is useful to study the role of the confrontation aspect in the four remedial programmes, i.e. the elicitation of pupils' latent ideas and the demonstration of their lack of explanatory power. Elsewhere, we report on the results in relation to the remedial programmes 1, 2 and 3 (Licht, 1989). A comparison of the testresults on the occasions 1 and 2 leads to the following conclusions: 40% less CC-thinking (a decrease of 10% out of 25%), 30% less CS-thinking, 50% less LS-thinking and 67% less CV-thinking after the two or three hours of remedial education. The results after remedial programme 4, which includes the computer simulation, are quite promising. The comparison of the testresults on the occasions 2 and 3 gives an extra impulse to do a more in depth study in the near future on the learning effects of the simulation programme. This comparison leads to the following conclusions: 86% less CC-thinking (2% out of 15%), 54% less CS-thinking, 70% less LS-thinking and 30% less CV-thinking. Between the second and the third occasion the classroom demonstration of the computer simulation took place and also the related explicit confrontation between the macro-micro relationships and the other intuitive ideas, i.e. CC-, CS- and LS-thinking. We may conclude that these classroom activities contributed to a change in intuitive ideas as well.

Compared to the remedial programmes 1, 2 and 3 in which we use operational concepts like voltage and current to promote conceptual change, programme 4 with the macro-micro model seems to be the most succesful. This relative success is demonstrated not only among the pupils who were referred to this specific remedial programme, but also among the students to whom other intuitive ideas were attributed.

Results on an assessment task

We limit ourselves to the discussion of those assessment results which cast the most light on the specific contribution of the macro-micro relationships in the enhancement of the conceptualization concerning the three target concepts voltage, current and electrical energy. One of the questions of the final assessment test concerns an electric circuit with a battery, two light bulbs and two switches. Seen from the perspective of the textbook the situation with the switches is completely new. The subquestions concern the way in which the changing of switches in the circuit might affect the relative brightness of the bulbs. We emphasize that the questions could be answered directly in terms of voltage and current, so it is not necessary to use the macro-micro model. The results were the following:

- 30% of the pupils scored more than 80%, of which 75% used the macro-micro model;
- 60% of the pupils scored more than 50%, of which 61% used the macro-micro model;
- 40% of the pupils scored less than 50%, of which 95% did not use the model.

Also from these data it is clear that, for a lot of pupils, the macro-micro model can serve as an effective tool for qualitative reasoning in electric circuits already during the operational stage of the educational process.

6. CONCLUSIONS AND DISCUSSION

We certainly do not mean to imply that the use of a diagnostic test and related remedial learning programmes is necessary within every area of physics education. However, the construction of scales of items has a benefit in that it contributes to a better identification and a more precise categorisation of errors and conceptual difficulties. We have not only applied this method to the domain of electricity but also to the domain of mechanics (Licht & Thijs, 1990). It appears that pupils do not simply make incidental mistakes, but that they show patterns of conceptual difficulties and ways of reasoning which they can recognise the moment they are confronted with these patterns in a remedial learning process. The precision of this characterisation increases throughout secondary education. This means that pupils in higher forms use preconceptions more consistently in problemsolving situations than pupils in lower forms. We see this as an important reason why pupils in the higher forms are more open to conceptual conflicts and to demonstrations intended to reveal the gap between their ideas and expectations on the one hand and a physical explanation of a certain phenomenon on the other. Therefore, our conclusion is that the use of a test and related remedial learning programmes could be effective in the higher forms of secondary education.

We are also rather cautious about the possible learning effects of the computer simulation programme on macro-micro relationships for all forms of secondary education. Although some teachers already use the model in the lower forms, our first impression, based on ten interviews with younger pupils working with the programme, is that we have to force them too hard into the way of reasoning demanded by the programme. We certainly do not have this impression with fourth-form pupils. After only 15 to 20 minutes, they are already able to apply correctly the concepts of electron flow and electron densities to new electric circuits. Teachers see the programme as a good opportunity to supplement their (most of the time weak) existing methods of explaining the difference between voltage, current and energy.

The general conclusion is that the macro-micro model is an effective tool for most of the pupils in the fourth form for solving qualitative questions with respect to changes in voltage and current and changes in phenomena such as the brightness of bulbs or the speed of electric motors. The model provides pupils with acceptable explanations of the regularities found during the descriptive stage of the educational process.

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LOOKING BACK AND FORWARD: REPORT OF REFLECTIONS AND DISCUSSIONS

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1. THE SEMINAR IN RETROSPECTIVE

Dr. Robin Millar and Dr. Adri Verdonk had been asked by the organizers to reflect on the seminar. After their presentations a first plenary discussion was held, chaired by Dr. Peter Voogt.

Reflections of Robin Millar
Millar started by saying that he tried to base his points on informal discussion with a number of participants during the seminar. First he identified three areas of agreement and common ground shared by a majority of the participants of the seminar.

1. Participants are interested in teaching *something* and want to help children to learn *something*. Their purpose is to communicate science to children. The agenda is *constructivism* and NOT *discovery learning*.
2. Participants agree that it is useful to think of learning as the learner constructing meaning, NOT as the teacher transmitting a body of knowledge.
3. Participants agree that it is worth talking to each other and continuing to talk to each other.

Secondly, he mentioned three areas where differences of emphasis or approach emerged during the seminar.

1. What kind of understanding should be promoted: scientists' science or science for everyday living? Questions to be further discussed are: Do we agree; Could we ever agree; Is agreement necessary if our discussions are to be fruitful? His personal answers to these questions are: no, no and no.
2. What has been the progression in children's understandings:
   - is there evidence for common progressions (trajectories)?
   - if there is such evidence, what characterise them and at what level (general or domain specific)? Even views on 'domain' appear to be different.
3. Is the promotion of conceptual change ad hoc, does it follow principles, and are these principles general or domain specific?

Further discussions are needed in order to resolve these questions or to clarify the differences.

His third point regarded the participation of both physical scientists and biologists in the seminar. He asked the question: Was I present at one seminar or at two seminars held at the same place. Related to this he raised the following three questions:
- to the biologists: In what ways was the presence of the chemists and physicists useful to your discussions and helping you in aspects of your thinking?
- to the chemists and physicists: In what ways was the presence of the biologists useful to your discussions and your thinking?
- to everyone: Does this tell us anything about the idea of "integrated science"? Is science one thing or several things?

A final set of Millar's points were of a more practical nature and dealt with the organisation of the seminar and of future seminars of this kind.
- Its value: yes.
- Its size: about right, certainly no larger, perhaps smaller.
- Its topic: there was some unclarity about the theme: What does 'macroscopic' mean? What is 'microscopic'? 'Children's views on matter' may have been a better theme; a specific topic is better than a general one.
- Its organization (in a descriptive, not valuative sense): the workshops were felt to be very useful as the smaller size allowed for more and more frank discussions; the plenary session of Wednesday was better than the one on Monday, perhaps due to the smaller group, the order of the room (rectangular instead of common lecture theatre arrangement of seats), and better knowing each other; the format of the working papers caused some problems as many participants had not read the papers (of ten pages each) in advance and as 20 minutes was too short to present them; it might be better, perhaps, to write only a synopsis in advance and to give an oral presentation of 20 minutes during the seminar; the atmosphere was good informal, using first names quickly, for instance.
- Further communication, co-operation and collaboration after this seminar or in between seminars: his experience of working with some people in the Centre in Utrecht is that we should recognize that collaboration takes time (you first have to know what the others are doing); it requires working on a project together, based on mutually shared interest and curiosity; and very pragmatically: using e-mail has shown to be very useful and he suggested to exchange e-mail addresses.

Reflections of Adri Verdonk

In his reflection on the seminar, Verdonk tried to answer two general questions: What have I learned?, and: What have I missed?. He made the following personal points, based on attending 16 presentations and two plenary discussion sessions.

Firstly, he learned a great deal about scientific models and models in science education. He noticed that we limited ourselves to 'materialized' particles and to their representation in space and time. So he found himself in a familiar scientific environment with concepts such as movement, size, space and so on. But this representation hindered him to make the transition from mechanics to fields such as electricity, quantum-mechanics and thermodynamics. He experienced some problems both with his scientific concepts and with his educational concepts.

In considering models he found it important to put the relation between models and 'facts' on the agenda. We discussed the sequence between models and facts: should we induct or deduct? And we talked about the relation between models and ways of reasoning and about language problems. He also learned about this from other participants.

In the discussions he had no problems to understand other participants' views in discussions in which they spoke as physicists and chemists, or as teachers of these disciplines. Learning is possible as long as you understand each other. More problems arose in trying to understand participants' views as regards educational research in science, as will be outlined below.

Secondly, the question of what he missed, not meant to criticize, just to give a personal view.

- Although a clarification of views on science, science education and educational research was given, the ways in which these views influenced research questions, methods and results were not made explicit.
- We always spoke about the conceptual change of pupils, but we ourselves also have concepts, we develop these and restructure them; we should have paid more attention to the conceptual change of teachers, curriculum developers and researchers as regards their views on education and on science.
- The legitimation of the educational research experiments was lacking: why asking particular questions and no others?

He ended with a question to all participants: how to proceed from a group of individuals thinking about science education to a group of researchers in this field?

Plenary discussion

In the discussion after both presentations the following points were raised by various participants. It should be noted that these points expressed views of individuals, as time did not allow for efforts to reach consensus.

- Is there really a difference between 'scientists' science' and 'science for everyday living', as suggested by Millar? Is it not a difference only in purpose of teaching?
- Long ago a choice between teaching 'scientists' science' and 'science for everyday living' has been made; so a tradition was set of teaching 'scientists' science' in schools; the question is now how to escape from this tradition.
- Teaching biology inevitably involves talking about chemistry and physics; and also, how biologists handle particles has implications for

teaching physics and chemistry; so there should have been a plenary session about the implications of particle ideas for teaching biology; a discourse on this issue is recommended for future seminars.

- How can we avoid that learning from a constructivist point of view leads to a destructivist view of life? This question came up with one of the biologists, listening to the contributions of chemists and physicists; from a biological point of view looking at living matter is more than breaking up cells into particles.
- Biology tends to synthesize much more than the two other sciences; one of the chemists admitted that chemistry education focusses too much on 'separating' ("schei-kunde") and not enough on creating, on synthesis; the system approach in biology is also important in chemistry education.
- Biology and chemistry/physics have been separated along the line of dealing with living or dead matter; this is of course very artificial.
- In some countries biology educators never meet with other science educators; this opportunity therefore was welcomed.
- It may also be important to look at the relation between chemistry and mathematics; this participant felt that the integration between chemistry and physics education should have priority.
- It is important to look at the level of generality in looking at the relation between physics, chemistry and biology; only general or specific levels should be avoided: we should think up and down between these levels.
- Is it fair to put constructivism and discovery learning opposite each other, as Millar did, because guided discovery could also be seen as a constructivist method; Millar defended opposing the two views with reference to well documented trends in the UK.
- In response to Millar's suggestion to take a more specific topic it was argued that perhaps next time we should take an even more general topic, such as 'steps in conceptual development'; we should then focus on conceptual change and avoid discussions on specific subject matter.
- In future seminars more attention should be paid to problems teachers have with using the new materials which we developed, to an analysis of the concepts we use as educational researchers and to a comparison of research methods.

Finally Millar thanked the organizing committee, the Centre for Science and Mathematics Education, the staff of Woudschoten and the sponsors on behalf of all participants. He concluded by saying that we have been able to communicate as people.

2. LOOKING FORWARD

Finally, a second plenary discussion was specially devoted to the question of how to proceed. First Lijnse briefly summarized what had been the aims of the organisers for this seminar. That was first of all to bring together a relatively small number of people, working actively in the same field of research in science education, in order to stimulate in-depth discussions about each others work on a chosen topic. In view of this, one could ask whether the number of participants and the diversity in backgrounds had not been already too large and whether the topic for this seminar was well chosen.

A second long term aim however was that in inviting people from Europe and Israel only, thus from "nearby", could this informal small-scale seminar not become the first in a series of regular events. Is there not a need for european researchers in our field to meet regularly and be able to discuss our work, as the regular large scale conferences are in general not suited for this purpose?

Before the seminar, the organisers had asked a small number of very senior researchers about their opinion concerning this need, and in general their reactions supported this idea. Thus, if the participants could agree on this need as well, the problem becomes how to make sure that such small-scale, specific topic-oriented meetings will indeed take place regularly? Who will organise a next one? What are appropriate topics? Etc.

In the discussion there was much support for the need of seminars like this. We need more communication in Europe, it was said. Some organisational possibilities were mentioned, as a SIG of EARLI, in cooperation with EPS, or to start a new organisation. No clear common opinion was reached on this, apart from the feeling that the last possibility was probably too ambitious, the second too much concerned with physics and the first too general.

Concerning the size of the seminar it was remarked that it could be called "meso-scale", for which there is indeed a role to play. At such meetings one may have sufficient opportunity to discuss and learn to know each other sothat real cooperation, which necessarily occurs in small groups, thus at the "micro-scale", may emerge from them. That would be one of their main purposes.

Concerning the topic, opinions differed. Some said that the micro-macro theme was well chosen and would welcome a next similar seminar, e.g. on the teaching of energy. This idea was supported, provided that the program would contain more small group work.

Others however emphasized that the next theme should be more general, though with a sharp leading question, e.g. how to reach conceptual change in science teaching.

A unification of both opinions was also suggested in the idea to make a link between focussing on subject matter and on a more general theme. A next topic could then be something like: how to induce conceptual change in the teaching and learning of energy (or in another subject field).

In doing so, it was felt that the participants would contribute more from a common perspective, then had been the case in the present seminar. As a possible fruitful way of working it was suggested that participants should bring along a small piece of teaching material (1 or 2 pages) in which a new concept is introduced in relation to research findings. The central focus could then be how this is actually done, if some generalities can be formulated from such examples and how relevant this kind of research is for the teaching practice. Several people supported this as "quite a nice idea".

Thus far the general discussion seemed to be rather fruitful. However, when the question was put: "Who is going to organise a next seminar?", the rest was silence. Although, as described, the general idea of having more seminars was supported, nobody present was as yet able to offer to organise one. Therefore it was agreed that people from the CSME in Utrecht would spread the idea and try to find a next organiser. In case this would turn out to be an impossible task, they will consider to do it again themselves! This was welcomed as an "optimal offer". As a result, everybody seemed to be happy again, and the seminar was closed!