M.J. Vollebregt

A Problem Posing Approach to Teaching an Initial Particle Model

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A Problem Posing Approach to Teaching an Initial Particle Model

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A Problem Posing Approach to Teaching an Initial Particle Model

Een probleemstellende benadering voor het onderwijzen van een aanvankelijk deeltjesmodel

(met een samenvatting in het Nederlands)

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1 Introduction

1.1 Understanding the particulate nature of matter: an important educational goal

During the past fifteen years I have met many people who consider science, and especially physics, as the most difficult and uninteresting subject in secondary education. More recently, when I described the topic of my thesis to some of these people, they generally commented that "it was about time that someone did something about that". Their physics lessons had started by dealing with molecules and atoms, but a lack of understanding of this material caused them to lose interest in the subject right from the beginning.

If theory concerning molecules and atoms is really so difficult for youngsters to understand, then why should pupils learn about such particle models? Basically, we see three main reasons. Firstly, particle models are very important in science. Almost all major scientific journals contain articles in which knowledge about the behaviour and/or structure of particles is essential. Assuming that transfer of cultural heritage is one of the main aims of education in general, in science lessons pupils should be taught about the main lines and results of scientific work, thus including such particle models and the way in which they are used. Secondly, in general, models are very important in science. Scientific knowledge is developed using models and this knowledge has an influence on our society. Not only in the sense of useful products, such as new medicines or faster means of communication, but also, for instance, in the field of decision-making concerning the environment. If education wants to prepare pupils for becoming responsible citizens, they need to gain some understanding of the nature of scientific knowledge, and thus of the hypothetical nature of models and how these function in the framing of predictions and explanations. Particle models can serve as an important example by means of which such aspects of the nature of scientific knowledge are taught.

Thirdly, the process of modelling in itself is an important and fruitful activity in science. Scientists build and develop models because this leads to a better understanding of their surroundings. More specifically, they frame hypotheses about the way in which observations should be connected to a model and about how the behaviour of one aspect of the model influences that of other aspects. They test these hypotheses, for instance by comparing them with other possibilities, by thinking through hidden consequences or by making predictions that can be experimentally verified. Particle models can serve as an important example by means of which pupils themselves may experience this process of modelling. These three reasons produce a first general indication of an educational goal, i.e. pupils should learn about and understand the particulate nature of matter, which is pursued in practically all physics curricula and textbooks all over the world. This is a goal, however, that is difficult to reach.

1.2 Results of research in science education

Pupils' ideas

Over thirty years of research in science education has shown that understanding scientific subject matter is often far from easy. Initially, it was found that many pupils hold "misconceptions" concerning various scientific topics, i.e. they often incorrectly assimilate the formal models and theories that they are taught. For instance, Viennot (1979) found that even many university students applied Newton's laws incorrectly. Similar problems were found by other researchers in various fields of science, such as the mole concept, thermodynamics, electricity and light. Many of these "misconceptions" were not expressed by only a few pupils but appeared almost to be commonly shared. Such "misconceptions" were also found with respect to pupils' knowledge about the particulate nature of matter. Thus, the results of research in science education described above give a first indication of the educational problem that is faced in this thesis.

On further analysis, these "misconceptions" were interpreted as being mainly due to the negative interference, in the process of learning, of so-called "preconceptions", i.e., pupils' conceptions about a particular scientific topic before having been formally taught about it. In the literature, these "preconceptions", which over the years were increasingly considered to be embedded in larger frameworks, were interpreted as being scientifically largely incorrect. Furthermore, it was argued that the teaching process largely ignored their existence, or did not deal with them appropriately (Driver & Easly, 1978; Driver, 1981).

The idea of negatively interfering scientifically incorrect preconceptions makes it understandable that much research has been done on trying to describe them (cf. chapter 2 for such research on the particulate nature of matter) and on designing teaching approaches that could deal with them. Both can be viewed as in line with Ausubel's dictum: "Find out what the learner already knows and teach him accordingly" (Ausubel, 1968, p.337).

New approaches inspired by educational constructivism

The development of such better teaching approaches has been largely inspired by educational constructivism (cf. chapter 3). This task, however, has appeared to be far from easy, for educational constructivism is rather a view on learning than a handbook which prescribes how instruction may be improved. Basically, it offers only two important guidelines: take pre-existing ideas into account, and make pupils more actively involved in the process of teaching and learning. It does not, however, indicate how such a "bottom-up" approach should be designed, nor how this will subsequently encourage pupils to arrive at the remote educational goals, i.e. the understanding of a specific scientific theory.

Several strategies have therefore been developed, both at a general level, such as the conceptual change strategy (Driver & Oldham, 1986), and at a more content specific level, resulting in new teaching approaches for all kinds of topics. Especially these specific teaching approaches present possible ways to engage pupils in a more active learning process. As most of these attempts have only limited results however, the educational problem outlined in this thesis remains unsolved yet. In chapter 2, the shortcomings of several approaches to teaching and learning particle models will be analysed in detail.

In our view, a major problem with research on pupils' pre- and misconceptions is that it often seems to misinterpret pupils' ideas, ascribing to them incorrect beliefs about the world which they do not hold (Klaassen, 1995). This implies that teaching approaches that focus

on a process of conceptual change start from an inadequate point of view (Klaassen & Lijnse, 1996). In our view, pupils' pre-knowledge, is largely correct and therefore an adequate and productive starting point for further learning. The educational problem then becomes how to make pupils able and wanting to develop their knowledge in the direction that is set by our educational goals.
At the Centre for Science and Mathematics Education at Utrecht University (CSMEU), several "bottom-up" strategies for teaching and learning specific scientific topics have been developed. One of these is called a "problem posing" approach, which has been applied to teaching the topic of radioactivity (Klaassen, 1995). Apart from building on knowledge that pupils have previously developed, this approach focuses heavily on inducing content related motives that may drive their process of learning in such a way that the educational goals are better reached. In other words, the approach aims to bring pupils in such a position that they themselves develop good reasons to extend their knowledge in the way that was intended by the designers. Although this strategy has only been applied to the topic of radioactivity, it seems to be a promising one. In particular, because it suggests how pupils' ideas can be taken into account, how to make pupils actively involved in the process of teaching and learning and, moreover, how to encourage them to further develop their own ideas towards the educational goals.

1.3 Research questions

The central problem of this thesis

As discussed in the first section, understanding the particulate nature is an important educational goal. On the other hand, such understanding is difficult to reach and new teaching approaches are, to our opinion, not sufficiently adequate or, in the case of "problem posing", not yet applied to this topic. Thus, the central problem of this thesis is the design of an empirically supported process of teaching and learning, during which pupils:

- learn that, according to science, matter consists of specific particles, and learn to use such particle models in order to explain and predict several relevant phenomena;
- and come to understand the nature of particle models and scientific modelling.

This problem can be considered a specific example of a more general problem, namely how processes of teaching and learning in science education may be designed, so that pupils consequently reach an adequate understanding of scientific knowledge, the nature of science and/or the process of modelling. Therefore, the results of this dissertation should also provide some preliminary indications as to how the more general problem may be solved.

The research method and questions

The central problem presented in this thesis has been tackled by means of "developmental research". At a general level, this method of research is described by Gravemeijer (1994) and Lijnse (1995). Such research starts from explicit views on teaching and learning science, based upon which specific choices are made concerning the way in which, for a specific topic, the process of teaching and learning should take place. Subsequently, tests are performed, by means of a specific teaching sequence, to determine whether it is possible to actualise such a process and whether it leads to the intended aims. The results of such a test, in turn, contribute to the development of ideas concerning the way in which the

teaching and learning should take place. Developmental research can thus be characterised as a theory-driven, cyclic process, of designing and evaluating.
The views upon which the research reported in this thesis is based, will be discussed in detail in chapter 3. On the basis of these views, two main choices were made concerning the process of teaching and learning:

- it was attempted to design a problem posing approach;
- guided by teacher and teaching materials, pupils were given the opportunity to (further) develop a particle model themselves, i.e. they were to become involved in a modelling process as an aim in itself.

The teaching sequence was designed following extensive analysis of research results concerning pupils' ideas about particles, and a thorough analysis of innovative teaching materials dealing with this topic. Subsequently, it was repeatedly tested and revised. Evaluation of the actual processes that took place in the classroom, and subsequent theoretical reflection, will be used to answer the following questions:

1. *To what extent did we succeed in designing a process of teaching and learning during which pupils reach the intended aims?*
2. *To what extent does the course of this process of teaching and learning empirically support the adequacy of the choices that were made?*

1.4 Contents of this thesis

In chapter 2, the results of research into pupils' ideas about the macroscopic behaviour and particulate nature of matter, as well as about the nature of particle models and of science in general, are reported and reflected upon. In addition, some innovative teaching materials that deal with the particulate nature of matter are analysed. The findings illustrate why the central problem outlined in this thesis is still not solved satisfactorily, resulting in five specific problems. In chapter 3, the views on teaching and learning physics, and on particle models, upon which the research presented in this thesis is based, are described in light of our search for improvement of current teaching about particles. These are followed by initial suggestions for possible solutions to the five remaining problems.
The specific teaching sequence that was constructed on the basis of these suggestions is discussed in chapter 4. The design is accounted for by means of the results of the previous chapters. This chapter contains examples of expectations of the course of the actual process of teaching and learning in the classroom, as well as illustrations of activities. In chapter 5, the actual process of teaching and learning is described and analysed, accounting for possible deviations of the expected course of events.
Finally, chapter 6 deals with evaluation of the approach. Pupils' and teacher's opinions about the approach are summarised and discussed. In addition, it is evaluated to what extent pupils have reached the intended aims and to what extent our choices have been adequate. As such, this evaluation constitutes an answer to the above research questions. In reflection on these answers, a structure for the introduction of a particle model in secondary physics education is presented. Finally, some suggestions are made concerning teaching and learning physics in general.

2 The introduction of particles: still an unsolved problem

2.1 Introduction

The previous chapter indicates that the teaching and learning of an introductory particle model in physics education is inadequate. In the Netherlands, a previous study into pupils' ideas about particles showed that, after two years of physics education, many pupils did not understand the particulate nature of matter appropriately (Vollebregt & Lijnse, 1993). These results supported another investigation, concerning the way in which the topic is taught in physics textbooks (Vollebregt & Lijnse, 1992). In the latter, it was found that a particle model is often presented as a collection of facts, and pupils' ideas about matter are not sufficiently taken into account. Together, these results indicate that the topic of particle models asks for further attention. In this chapter, the problem is described in more detail, using examples from the literature.

In several countries, investigations have been conducted towards what pupils do and do not understand about the nature of matter. Results of such research are first reported and discussed. Considering the aims of this thesis, the analysis is focused on the following question:

What was reported about pupils' ideas about (the particulate nature of) matter and about the nature of science and (particle) models?

The answer to this question is given in section 2.2. When pupils' ideas about these issues are known, these can be taken into account in the design of a process of teaching and learning about particles. How such attempts have been made by other researchers, to what extent they have succeeded and, subsequently, what can be learnt from their approaches, is discussed in section 2.3. This section aims to answer another important question, namely:

Which content specific educational strategies were used to improve the introduction of particle models, and to what extent can we build on these?

In section 2.4, the answers to both questions are used in order to further specify the central problem approached in this thesis.

2.2 Results of research into pupils' ideas

2.2.1 Introduction

In this section, the results of research into pupils' ideas are analysed. Three areas of research were selected. Firstly, pupils' ideas about macroscopic behaviour of matter, as understanding a particle model adds to this knowledge. Secondly, research towards ideas about the structure of matter and, thirdly, ideas about the nature of science in general and, more specifically, about the nature of (particle) models. These results are summarised in sections 2.2.2 and 2.2.3, and interpreted in section 2.2.4. In the interpretation we will make a distinction between, on the one hand, pre-existing ideas and, on the other hand, misconceptions that were developed as a result of education. The first should be taken into account in new teaching strategies, whereas the latter should be prevented.

2.2.2 Pupils' ideas about matter

Reported ideas about macroscopic states of matter

Hibbard and Novak (1975) reported that uninstructed children, in the first-grade, used observable "bulk properties" of matter as distinguishing characteristics of solids, liquids and air. From a scientist's point of view, many of these properties are directly related to the differences in density or penetrability of the three states of matter. Other examples of such properties are wet-dry, cold-warm and visible-invisible. Stavy and Stachel (1985) stated that, in their research, children often did not classify substances as "solid" or "liquid" according to the school science theory, however this classification did improve with age. Furthermore, many children were not able to make a proper distinction between the material of which an object was composed and its state. Their sample consisted of 200 children, 5 to 12 years old:

> Children recognize similarity between two liquids presented to them at an earlier age, and to a greater extent, than they recognize similarity between solids. Also, the use of the word 'liquid' is more common and starts at an early age. (...) From the age of five, children have more success in classifying liquids; liquid meaning 'it pours.' (...) Rigid solids are correctly classified from the first grade on; non-rigid solids are correctly classified by almost half the population at all ages, while the rest of the population regards them as an intermediate group; powders are usually unsuccessfully classified (...) as liquids because they pour, or as an intermediate group. It can be inferred from these findings that 'solid' is understood by children as a rigid material. (Stavy & Stachel, 1985, p.419)

These results have been confirmed by the outcomes of Jones and Lynch (1989).
Pupils' ideas about the gaseous state were investigated by Séré (1985, 1986). From the results of her research (sample of 600, age about 11 years old) she concluded that children know that air, although not visible, exists and circulates. Little is known about other gases:

> Everyday life gives rise to few problems about air and gas. Apart from winds and draughts, air appears invisible, and leads to few perceptions. However, children often know where air is located. They imagine some erroneous repartition of it and believe it to be in motion in containers as well as in the atmosphere. Such motion is more frequent when a source of heat is present. Pupils' spontaneous interpretation of experiments (..) leads to the conclusion that (a) in relation to gases, pupils aged 11 years have not yet acquired the conservation of matter; (b) pupils sense intuitively that 'something' changes when the pressure of a gas changes; such changes are frequently described in animistic terms. (Séré, 1986, p.413)

As examples of erroneous repartition of air, Séré (1986) mentioned that many pupils believed that air is more or less thick according to the places where it is found (e.g. around the objects present in air), and that air does not circulate in the same way everywhere (e.g. it can freely circulate in an open bottle but not in a closed one). Children also referred to hot air rising, but never to cold air sinking. Apparently, some children believed that "the more air there is, the lighter it would be." Their explanation was that objects float or bounce better when full of air. Most of them acknowledged that air exerts a force, but only when heated or during movement, in the direction of this movement. The animistic reasoning referred to by Séré, was visible in two different ways: firstly, as a way of speaking, with word usage such as "wants to..." or "tries to..."; secondly, in an analogical way, e.g. "If I were squashed in a box...."

Stavy (1988) conducted an interview study with 120 children, age 9 to 15 years old. Results of this study showed that children did not spontaneously develop a general idea of gas prior to instruction, because in their daily life they had access to a very limited number of gases. Their ideas were not consistent and changed according to the task. Especially young children were affected by irrelevant perceptual elements of the task.

More research has been conducted into children's ideas about changes of state (Osborne & Cosgrove, 1983; Bar, 1989; Russell Harlen & Watt, 1989; Stavy, 1990; Andersson, 1990). Some of these researchers (Andersson, Bar, and Stavy) have tried to categorise the outcomes. They have all pointed out that younger children do not necessarily believe that matter is conserved. Bar, for instance, found that 5 and 6-year-old children believed that after evaporation, the water had disappeared. According to Andersson, when pupils do believe that matter is conserved, their ways of describing a change of state can be divided into four categories.

- "Displacement", i.e. the object has gone to another place. Bar, for example, found that 7 and 8-year-old children believed that after evaporation the water had penetrated the floor or other objects. These children already believed that the amount of liquid is conserved but their view did not yet include a phase change.
- "Modification", i.e. the substance has not changed, only its physical properties. The disappearance of water is then explained by saying that it changes into vapour, that is, small invisible particles.
- "Transmutation", i.e. one substance has changed into another. In the study of Osborne and Cosgrove about boiling water, it was quite common for pupils to say that water was transformed into air. In addition, it was found that the children believed that, after evaporation and subsequent condensation of water, the result did not necessarily have to be the same water. A similar result was reported by Stavy and Stachel (1985): while describing melting, children said that a solid changes into water.
- "Chemical change", i.e. a chemical model is used to explain the change. This category mostly refers to pupils stating that water changes into oxygen and hydrogen.

Reported ideas about the structure of matter

Some children seem to have ideas about the structure of matter before learning about particles in school. Especially in situations such as dissolving and evaporation, these children appear to believe that, for example, sugar or water divides into small invisible particles (Pfundt, 1981; Bar, 1989). As stated in the previous section, such answers were classified by Andersson as "modification". Piaget and Inhelder (1974) called this notion "atomism". Contradicting outcomes were reported concerning the spontaneous use of particles in explanations following instruction. Novick and Nussbaum (1978) found that 64% of the pupils in their sample (n=152, age 13-14) spontaneously included particles in their drawing of air. Others (e.g. Stavy, 1990) have reported a much lower percentage. Whether spontaneously used or not, in several investigations only a relatively small percentage of pupils gave correct particle explanations:

> On average, less than one in five students are applying taught ideas about aspects of the particulate theory correctly. (..) At best, less than one in ten students have a thorough understanding of the topic. (Brook, Briggs & Driver, 1984, p.71)
>
> ..a significant portion of the sample failed to internalize important aspects of the particle model. (Novick & Nussbaum, 1978, p.278)

Basically, three ways were found in which pupils applied taught ideas in an unintended way. First of all, it has been reported (e.g. Brook, Briggs & Bell, 1983; De Vos & Verdonk, 1987) that in their explanations of macroscopic phenomena, pupils often attribute macroscopic properties to molecules and atoms: these particles can expand, melt, burn and they can be soft, liquid, coloured, alive, etc.

> The "granularity" of at least some stuffs is easily accepted but (..) the same set of causes and changes are often applied at both the macro and the micro levels. Whatever happens at the macro level is seen as a corresponding change at the micro level - the difference between the two is seen to be one of size and not nature. (Brosnan, 1990, p.208)

Secondly, pupils seem to forget which movement or which intermolecular distance or force is characteristic of the three states. For instance, Brook, Briggs and Driver (1984) have found that "some students think that forces exist between particles in the gaseous state", "some students think that forces do not exist between particles in the solid state" and "some students confuse the solid, liquid and gaseous states" (p.73-74).

Thirdly, pupils interpret the assumptions that are taught in an alternative way:

- the particles are not necessarily in continuous motion, e.g. they stop on cooling or at 0°C (Brook, Briggs & Bell, 1983); or the space-filling property of gases is not attributed to the intrinsic motion of particles (Novick & Nussbaum, 1978);
- hot particles move faster than cold particles (De Vos & Verdonk, 1987);
- the space between the particles is either filled, e.g. with air, other particles, or the substance itself, or it is negligibly small (Brook, Briggs & Bell, 1983; Novick & Nussbaum, 1978; Andersson, 1990);
- the magnitude of forces between particles changes with temperature (Brook, Briggs & Bell, 1983).

Rozier and Viennot (1990) have described that a specific way of reasoning is often used in giving particle explanations. They termed this way of reasoning "linear causal reasoning": one cause is considered enough to explain a given effect, or simultaneous varying variables ("causes") are put in a chronological cause-effect relation. In particular, the mean distance between particles and their mean kinetic energy is often combined to an undifferentiated notion called "thermal motion", and it is commonly accepted that this thermal motion is higher in gases than in liquids and larger in liquids than in solids. For instance, in a study of Rozier (cf. Rozier & Viennot, 1990), 69% of the students (n = 181, university level) believed that in thermal equilibrium, during liquefaction, the mean kinetic energy of the molecules of the gas is larger than the mean kinetic energy of the molecules of the liquid. Another frequently used argument, in this respect, is that molecules need more room to move faster. Secondly, in several cases the number of variables is reduced. In other words, the explanations consist of linear chains: one cause→one effect where more causes ought to be considered. For instance, adiabatic compression is explained without taking a change in mean speed of particles into account. Also, the lower air pressure at higher altitude is explained without reference to the lower mean speed of the particles.

2.2.3 Pupils' ideas about the nature of science and models

The nature of science most commonly refers to the values and assumptions inherent to the development of scientific knowledge. Driver et al. (1996) have made a distinction between "characterisations of the purposes of scientific work", "views of the nature and status of scientific knowledge" and "views of science as a social enterprise". In this section, only literature that falls into the first and second category will be discussed, as far as it concerns:
- aims of science/models;
- development of scientific knowledge/models;
- an appreciation of the hypothetical nature of such knowledge/models.

In this restricted area of research many studies have been carried out, with an emphasis on pupils' views about the nature of theory and its relationship to evidence. First, the findings of three different investigations will be summarised (Carey et al., 1989; Leach, 1996/Driver et al., 1996; Grosslight et al., 1991), followed by some results of other research.

Three reported frameworks

The research that was conducted by Carey et al. (1989) focused on epistemological views of grade 7 (12-year-old) pupils, prior to and after exposure to a teaching unit which was especially developed to introduce a constructivist view of science. A clinical interview was used to assess the understanding of 27 pupils about the nature of scientific knowledge and research. As a result of their investigation, Carey et al. have proposed four broad "bands" into which pupils' epistemologies can be grouped:

> In level 1, the students make no clear distinction between ideas and activities, especially experiments. A scientist 'tries it to see if it works'. The nature of 'it' remains unspecified or ambiguous; 'it' could be an idea, a thing, an invention, or an experiment. The motivation for an activity is the activity itself, rather than the construction of ideas. The goal of science is to discover facts and answers about the world and to invent things.
> In level 2, the students make a clear distinction between ideas and experiments. The motivation for experimentation is to test an idea to see if it is right. There is an understanding that the results of an experiment may lead to the abandonment or revision of an idea; however, there is yet no appreciation that the revised idea must now encompass all the data - the new and the old. The goal of science is understanding natural phenomena - how things in the world work.
> In level 3, as in level 2, students make a clear distinction between ideas and experiments, and understand that the motivation for experiments is verification or exploration. Added to this is an appreciation of the relation between the results of an experiment (especially unexpected ones) and the idea being tested. Level 3 understanding recognizes the cyclic, cumulative nature of science, and identifies the goal of science as the construction of ever-deeper explanations of the natural world.
> (...) level 0 (...) students seem not to consider the information-seeking aspects of science at all. (Carey et al., 1989, p.520-521)

Almost all pupils were at level 1 before the teaching programme started, with modest improvements resulting from teaching (improvement averaged half a level).
As a part of their research, Leach (1996) and Driver et al. (1996) have designed one task to investigate pupils' characterisations of the purposes of scientific work and four tasks to determine their views of the nature and status of scientific knowledge. Approximately thirty pairs of pupils were interviewed at each of three age points (9, 12, and 16 years) for each task. In their analysis, they have noticed some common features of pupils' reasoning occurring across different probes. This resulted in a general typology of the distinct ways in which the nature of scientific knowledge is represented in pupils' discourse, although

this framework does not describe patterns in reasoning by individual pupils:

> Phenomenon-based reasoning: Description of particular phenomena and possible explanations of the cause were sometimes not distinguished.(...) For such students, testing appears to involve observing the behaviour of phenomena, and scientific knowledge is a description of such phenomena. In effect, no clear separation of theories, explanations, and descriptions was apparent in such responses.
> Relation-based reasoning: Controlled intervention in phenomena, involving the manipulation of key variables, was sometimes seen as leading to knowledge about the cause of particular phenomena. (...) Although theory/explanation and data/evidence were separated in such responses, an answer to the question was thought to emerge in a straightforward way from the data. In addition, explanations of causation were constituted in the same terms as descriptions of behaviour: theories involving new, unobservable entities were not posited.
> Model-based reasoning: Some students' responses suggested an awareness that theories are conjectural, and that enquiry involves the evaluation of theories or conjectures in the light of evidence. (...) Posited theories and data which could be collected and used in evaluation of theories were separated in such responses. (Leach, 1996, p.276)

Both Leach and Driver et al. have emphasised that this framework does not represent a hierarchy, except in terms of complexity of the reasoning involved. They have argued that in specific situations it is quite possible that any one of the three forms of reasoning may be the most appropriate to use. Nevertheless, the authors have noticed a development in pupils' reasoning. Overall, phenomenon-based reasoning tended to be used most by the youngest age group and relation-based reasoning was most common among 12- and 16-year-olds. Although a small number of pupils at the age of 16 used aspects of model-based reasoning, statements tended to be "piecemeal and implicit" (Leach, 1996).
In the study of Grosslight et al. (1991) 33 7th-grade (12-year-old) "mixed-ability students" and 22 11th-grade (16-year-old) "honors students" were interviewed about their conceptions of models and their use in science. The researchers have identified three general levels of thinking about models:

> In a general level 1 understanding, models are thought of as either toys or simple copies of reality. Models are thought to be useful because they can provide copies of actual objects or actions. If students acknowledge that some aspects or parts of the real thing can be left out of the model, they do not express a reason for doing so beyond the fact that one might want or need to.
> In a general level 2 understanding, the student now realizes that there is a specific, explicit purpose that mediates the way the model is constructed. (...) The model no longer must exactly correspond with the real-world object being modeled. (...) However, the main focus is still on the model and the reality modeled, not the ideas portrayed per se. Further, tests of the model are not thought of as tests of underlying ideas but of the workability of the model itself.
> Finally, a general level 3 understanding is characterized by three important factors. First, the model is now constructed in the service of developing and testing ideas rather than as serving as a copy of reality itself. Second, the modeler takes an active role in constructing the model, evaluating which of several designs could be used to serve the model's purpose. Third, models can be manipulated and subjected to tests in the service of informing ideas. Thus, they provide information within a cyclic constructive process. (Grosslight et al., 1991, p.817-818)

It was found that the majority of 7th graders had pure level 1 scores. The rest were divided between the mixed level 1/2 (i.e. their answers included aspects of both levels) and the pure level 2 scores. Only about one quarter of the 11th graders had pure level 1 scores. The rest were evenly divided between the mixed level 1/2 and the pure level 2 scores.

Other findings

Lederman (1992) summarised the main outcomes of research into pupils ideas about the nature of science that was conducted before the nineties. Although some tests were eventually not found to be completely valid, Lederman argued that it was significant that all investigations yielded identical findings. The overall conclusion was that pupils do not possess adequate conceptions of the nature of science or scientific reasoning. They, for instance, believe that:

- scientific knowledge is absolute and its primary objective is to uncover natural laws and truths;
- scientific research reveals incontrovertible and essential absolute truths;
- hypotheses can be proven by verification;
- and scientific theories, with constant testing and confirmation, eventually mature into laws.

Griffiths and Barman (1995) have conducted interviews with 96 pupils from three different countries. They have found that laws are commonly seen as "superfacts" or as mature theories, that many pupils think that science does not change or just changes in instrumentation and technology and that most pupils seem to be convinced of the certainty of factual knowledge. However, half the sample believed that scientific work is theory-driven, half of the Canadian pupils mentioned the importance of new ideas as a reason why science changes, and three quarters of the whole sample, upon further questioning, were not quite convinced of the certainty of factual knowledge.

Duveen et al. (1993) have conducted a close study of pupils in five Key Stage 3 classes (11/14-year-olds) who were learning National Curriculum science with the help of special materials. Their results showed that many pupils at the start of Key Stage 3 believed that the outcome of an experiment is quite unpredictable and that a scientific theory may be considered a fact or just the (correct) experiment results. It was further believed that unanticipated outcomes to experiments may be taken to falsify the whole theory, while the role of imagination and evidence in theory building and using a model seems to be rarely understood. In addition, progress may be attributed entirely to technological improvements.

Concerning particle models, De Vos (1985) argued that by attributing known characteristics of macroscopic systems to molecules, pupils' models in many aspects become one with reality and are also considered as reality by these pupils. This conclusion was further illustrated by reported ideas about the structure of atoms. Klaassen et al. (1990), for instance, have found that pupils of middle ability in Dutch secondary education took the pictorial representations of atoms literally.

> 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). (Klaassen et al., 1990, p.307)

Other examples have been given by Griffiths and Preston (1992), such as the belief that molecules or atoms are flat.

2.2.4 Discussion

The previous sections included a number of research findings from the literature. At this point, it seems appropriate to address the problem of interpretation of such findings, which plays an important part in research. This problem has, rather recently, received renewed attention. For instance, Klaassen (1995) and Johnson and Gott (1996) independently have warned that, in many studies, pupils' ideas were probably misinterpreted.

Ideas about macroscopic behaviour of matter

Johnson and Gott have argued that the outcomes of research conducted by Stavy and Stachel (1985) should be considered with caution, for the tasks that were used in this research were not neutral, i.e. they inappropriately constrained pupils' thinking. For example, children who did not use the word "solid" spontaneously (this was for over 80% of the sample), were told that both a rock and a stick were solids. As a result, it may well be that the pupils were answering in a different manner to the scientific question of state, because of an induced alternative interpretation of the word "solid" to mean "a rigid object". The outcome that many pupils have difficulty in classifying non-rigid solids and powders, appears consistent with this analysis.

Similarly, pupils' language about changes of state should be considered with caution. For instance, "a child saying that something disappears may just be saying that he or she can no longer see it (which is accurate), without any implication of what it means has happened to it." (Johnson & Gott, 1996, p.573). In addition, it seems inappropriate to conclude that pupils really believe that water changes into air or a solid into water. For Andersson (1990) already admitted that "the word 'air' might also refer to an undifferentiated idea of something gaseous" and "another interpretation is that when the students say water they mean liquid" (p.17).

Thus it seems that, although they sometimes use words differently, and do not yet know how to classify scientifically, pupils do know much about the behaviour of matter from daily life. And this knowledge may be closer to the school science view than suggested in the literature. Most likely, their ideas have much in common with what Hayes described as a "naive theory of matter":

> There are different kinds of *stuff*: iron, water, 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 some things is *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 of changing a powder into a solid (but wetting it to get a paste, then drying the paste carefully, sometimes works). (Hayes, 1979, p.260)

Behaviour of gases is not incorporated in this theory, in agreement with the result that children know little about gases other than air. However, the reported ideas about air should, again, be considered with caution. The frequent reference to moving air is understandable since we usually do not notice air unless it is moving. As a consequence, younger children perhaps understand the word "air" as "wind" or "what people breath in and out". Questions about circulation and distribution (also in Andersson, 1990; Nussbaum, 1985) may thus not have been interpreted in the correct context. In addition, some of pupils' expressions are not necessarily scientifically incorrect, for a different meaning may well be attached to their words. For instance, the word "lighter" may refer to the ability to "stay up", given that it was included in statements that were connected to experiences with floating objects and bouncing balls. In addition, when children say that air only exerts a force when it is heated or during a movement, we cannot conclude that they believe that only in such cases the scientific expression "air exerts a force" is applicable. Instead, they may simply believe that only in such cases a visible event occurs that is caused by the amount of air considered (cf. Klaassen and Lijnse, 1996).

Ideas about the structure of matter

The variety in outcomes concerning the extent to which pupils spontaneously use particles in their expressions are very likely to be question-dependent. Furthermore, we can hardly expect spontaneous use of particles to occur frequently. Some researchers (e.g. Pfundt, 1981) have argued that, when pupils do make use of particles in their explanations prior to instruction, these particles should not be equalled to molecules or atoms. Indeed, such particles seem to be largely the result of a process of division instead of primary building-blocks that exist in matter all the time, for they are primarily used to account for situations in which matter is spreading and becomes invisible.

But even when pupils explicitly use the words "molecule" or "atom", they do not necessarily attach scientific meanings to these words. Moreover, the reported outcomes actually indicate that pupils mean something else by the word "molecule" than scientists do. We probably need to "attribute to them the (correct) belief that a substance can be divided into little bits that, apart from their size, are just like larger amounts of the substance (..) and accordingly interpret their expression 'molecule of...' as 'tiny bit of...'" (Klaassen, 1995, p.17). This interpretation is in line with the above comments of Pfundt (1981). More important, however, when we interpret pupils in this way, it is no longer surprising that they attribute macroscopic properties to "tiny bits of...". In fact, we all do. The remaining question is why pupils call these tiny bits "molecules".

This may very well be the result of education, either in school or by media such as television. For instance, in some older Dutch textbooks a molecule is presented as the smallest particle of a substance that still has all the properties of that substance (also cf. Andersson, 1990, with respect to Swedish physics textbooks) and sometimes it is even introduced as the product of a process of division (Vollebregt & Lijnse, 1992). Since it is not made clear what is meant by "properties" or "substance", pupils probably recognise this "molecule" as their "tiny bit of..". Even if such a definition is not given and pupils are only told that matter consists of molecules, being small particles, it seems likely that pupils will connect this new name to tiny bits. As long as they do not learn that there might be other kinds of particles than tiny bits, how are they supposed to know? This view of molecules as being "tiny bits" may be further stimulated by the absence in many textbooks of a clear distinction between substances, i.e. the macroscopic level, and atoms or molecules, i.e. the particle level (Andersson, 1990).

From this point of view it is quite understandable that pupils think that molecules can melt or be coloured. One can also explain why pupils sometimes either interchange the assumptions of the model that was taught or understand these differently. These assumptions usually do not coincide with the properties of tiny bits. Therefore it seems probable that pupils learn such assumptions by heart, without really understanding them and as a result interchange them, or interpret them in such a way that they at least make some sense for tiny bits, e.g.:

- the particles (only) move in case of a macroscopic displacement or if such a displacement is considered to be possible (e.g. in liquids and gases);
- if the temperature is higher the particles not only move faster but are also warmer;
- the space between them is not considered to be empty or it is negligibly small.

Linear causal reasoning may also be provoked by textbooks. It appears that incorrect arguments such as "molecules need more room to move faster" are frequently used in textbooks, also in the Netherlands (Vollebregt, 1991). In addition, teachers and textbooks tend to use incorrect story-like arguments, and teachers also appear to focus only on one cause when another important one should also be considered (Rozier & Viennot, 1990; Viennot, 1994).

The individual model that each pupil constructs thus becomes some sort of hybrid: parts of their correct knowledge of tiny bits are combined with taught aspects of scientific particle models. The result is probably no longer a correct model, not even for tiny bits, and it can best be understood as the consequence of teaching.

Ideas about the nature of science and models

Concerning interpretation of the findings of the research into pupils' ideas about the nature of science and models, some critical remarks should also be made. Duveen et al. (1993), for instance, have argued that the everyday meaning of "experiment", as opposed to the scientific meaning, indeed suggests an "unthinking activity with surprising results" (p.26). Also the everyday meaning of "theory" suggests uncertainty and guessing. This might explain why many pupils in the investigations that were mentioned before believed that laws are more certain than theories. Furthermore, Duveen et al. have pointed out that understanding the explanatory nature of theory is often inhibited by lack of clarity about the meaning of "explain". And finally, Ryan and Aikenhead (1992) have remarked that a confusion between science and technology might cloud epistemic views. In other words, the outcomes of some investigations might in fact represent pupils' ideas about the nature of technology rather than the nature of science.

When such remarks are taken into account, the following image of pupils' ideas emerges. Before pupils enter secondary science education, they may have already developed a naive view of the nature of science. Their idea of the aims of science can best be characterised as a vague understanding that scientists want to invent new things that make life more comfortable, e.g. new medicines or faster ways of transport and communication. In such a view scientific knowledge mainly changes by improvement of technology, which should be seen as an addition to, or refinement of, existing knowledge due to better equipment. This view of science corresponds to a stereotype image of the scientist, as it often is represented in tales and movies as well as television programmes and news bulletins. Since ideas about the work of scientists are rather vague at this level, the role and development of scientific models can hardly be understood. When asked, children will probably draw on their knowledge of models in daily life, which usually are examples or simplified copies of parts of their surroundings.

This rather vague image of the nature of science explains the above reported outcomes that were classified as level-1 or phenomenon based reasoning. The other reported findings mostly seem to be results of secondary science education. During these science lessons, pupils are often expected to perform controlled experiments from which they are supposed to derive new theory. Or the experiments are used as unambiguous proof to verify the theory (Vollebregt & Lijnse, 1992). Therefore, it is not surprising that pupils believe that knowledge can be derived in a straightforward way from data. When, in addition to this, particle models are presented as facts or as simplified copies of reality (Vollebregt & Lijnse, 1992), instead of asking pupils to use their own creativity in order to develop a model, we should not be amazed by results such as reported by Lederman (1992) and Griffiths & Barman (1995), and those that were classified as relation based reasoning.

2.3 Research based strategies for the introduction of particles

2.3.1 Introduction

The previous sections showed that many reported results of research into pupils' ideas about matter should be considered with caution and that pupils' pre-existing ideas may be far less incorrect than suggested. In addition, especially in the case of particle models, interpretation of the results indicates that many misconceptions occur as a result of traditional teaching. So taking these results into account foremost consists in designing a teaching strategy in such a way that the development of these misconceptions is prevented. In order to find indications for the way in which this could be achieved, several innovative approaches to teaching about particles were gathered and analysed. The following ones, which are well-known and clearly different from usual teaching methods, were selected:

- Children Learning In Science Project (CLIS, 1987; Johnston, 1990; Scott, 1992);
- Novick & Nussbaum (Novick & Nussbaum, 1981; Nussbaum, 1985, 1992);
- Séré (Séré & Moppert, 1989; Séré, 1990, 1992) ;
- Meheut et al. (Meheut & Chomat, 1990; Meheut, Chomat & Larcher, 1994; Meheut, 1995);
- Buck (1987, 1990, 1994 a).

To this list, an important innovative approach in Dutch chemistry education was added, namely "Chemistry in a thousand questions" (De Vos, 1992, 1993). In the review below, it is first analysed which model seems to be aimed at (section 2.3.3), and in which way it is introduced (section 2.3.3) and further developed (section 2.3.4). In addition, it is investigated how specific aspects of the nature of particle models are dealt with. Not all the selected approaches are discussed in each section. Instead, sometimes only one or a few are described as an example.

2.3.2 The model

All the sequences that were analysed deal with a model that does not essentially differ from the one that is generally used in secondary science education. The latter will be described first, followed by examples of differences.

The model that is generally used

By selecting statements from several research articles, De Vos and Verdonk (1996) have obtained a list of eight points which reflects how particles are usually treated in science education. The list is followed by the main phenomena that are usually explained by means of this model:

1. All matter consists of entities called particles. Individual particles are too small to be seen. They behave as hard, solid, and (except in chemical reactions) immutable objects. Their absolute dimensions and shape are usually irrelevant. In drawings the particles may be portrayed as small circles or dots.
2. Motion is a permanent feature of all particles, because of the perfect elasticity of collisions. There is a direct relation between the temperature of an amount of matter and the average kinetic energy of its particles.
3. In a gas the empty space between the particles is much larger than that occupied by the particles themselves. Particles of a gas in an enclosed space are evenly distributed, implying that gravity

has a negligible effect on them.

4. There is mutual attraction between any two particles, but its magnitude decreases rapidly with distance. In a gas the attraction is negligible, except at high pressure and at low temperature, when it may cause a gas to condense into a liquid or a solid.
5. In liquids and solids the particles are much closer together and subject to mutual attraction. In solids the particles are arranged in regular patterns, with each particle being able only to vibrate around a fixed position. In liquids the particles are irregularly arranged and move from place to place.
6. Different substances consist of different particles, but all particles of one substance are mutually identical. A mixture contains particles of two or more different species.
7. In a chemical reaction particles behave as if they consist of one or more subentities called atoms, which are conserved in the reaction. A reaction is therefore a rearrangement of atoms. Each of the approximately 100 chemical elements has its own kind of atoms.
8. An atom consists of a nucleus with a positive electric charge surrounded by a number of negatively charged electrons. Charged particles obey Coulomb's law. Chemical bond formation as well as electric currents are described in terms of the mobility of electrons.

In educational research as well as elementary science education, the particulate nature of matter is associated mainly with the following phenomena: solids, liquids, and gases and phase transitions; diffusion and dissolution processes; heat and heat transfer; electric currents; and chemical reactions. (De Vos & Verdonk, 1996, p.659)

This summary is in reasonable agreement with what is generally called a classical scientific particle model, for the particles are supposed to be invariant ("immutable"), and their positions and velocities are supposed to change due to mutual interactions, namely perfect elastic collisions and forces. According to the list, for charged particles these forces are determined by Coulomb's law and for other particles the attraction decreases when particles move away from each other. Apart from absolute dimension and shape, the summary does not mention any other properties of the particles. Furthermore, it remains vague as to which other connections between the model and macroscopic properties should be assumed, other than the one between the temperature of an amount of matter and the average kinetic energy of the particles. Apparently, only the latter is commonly explicitly referred to.

Differences between the models of the analysed approaches

The model that is taught in the sequence of CLISP seems to be in line with the first six points of the summary of De Vos and Verdonk. And, except for electric currents and chemical reactions, the model is used to explain the same phenomena. But in addition to the vague aspects of the summary of De Vos and Verdonk, the following issues are also only implicitly part of the model of CLISP:

- invariance of dimensions and shape;
- permanent motion due to perfect elastic collisions;
- the link between the temperature of a macroscopic amount of matter and the average kinetic energy of the particles;
- all particles of one substance are mutually identical.

De Vos developed a research based chemistry sequence, in which a model is taught that resembles the list of De Vos and Verdonk. Since it is foremost used to explain chemical reactions, this model does not explicitly mention that the particles do not change, and does not include empty space and perfect elastic collisions. In addition, as compared to the other approaches, it does not really emphasise differences in arrangements of particles of solids, liquids and gases.

Other research based teaching materials deal with a model that only, or mainly, applies to gases. Forces between particles therefore do not, or hardly, receive any attention. The model of Novick & Nussbaum basically incorporates only three aspects:
- matter consists of particles;
- between these particles there is empty space;
- there is a connection between macroscopic heat and movement of the particles.

The models of Séré and of Meheut et al. have more in common with the list of De Vos & Verdonk, but perfect elasticity is not mentioned, and in the sequence of Meheut et al. permanent motion is only implicitly suggested by a computer simulation. The sequence of Séré does not emphasise that the particles of the same substance are identical, whereas Meheut et al. only suggest this assumption by means of the drawings that are used. Furthermore, in the latter approach, pupils are encouraged to reflect on other connections between the model and macroscopic entities, in addition to the one between temperature and speed of the particles.
It largely remains unclear what kind of final model pupils are supposed to learn from the approach of Buck. His papers mainly show that pupils should learn that the particles have other properties than the systems that they constitute (cf. section 2.3.3).

Since the models of these approaches do not greatly differ from the one that is generally used in science education, the innovative character of such new strategies subsequently has to be reflected in the way this model is being taught. For it should be taught in such a way that the negative aspects resulting from traditional teaching methods, as reported in section 2.2, do not occur. These new ways of teaching the particle model are discussed below, starting with the way in which the model is introduced.

2.3.3 The introduction of the model

The transition from knowledge about the macroscopic behaviour of matter to the particle level is far from trivial. In particular, it appears to be quite difficult to make pupils understand that these particles are not tiny bits of matter. Therefore, the way in which it is attempted to let pupils make this transition becomes important to analyse.

Explanations of the observed properties of gases, liquids and solids

In the approach of CLISP, pupils first perform several experiments in order to become aware of their ideas relating to various properties of matter. Next, they participate in several games in order to understand the nature of scientific theories and the ways in which these are developed (cf. section 2.3.5). In addition, they are involved in the classification of solids, liquids and gases, which results in a pattern of properties of each state. In the central lesson of the teaching scheme, following classification, pupils are asked to generate a theory of what solids, liquids and gases are like inside, to explain why they behave in the ways that were described previously in the pattern of properties.
Based on the literature on pupils' ideas about matter, it can be expected that pupils either do not spontaneously use particles in their explanations or include assumptions in their model that do not agree with "the school science view". This is indeed what happened (Johnston, 1990). Furthermore, pupils who described matter in terms of tiny bits sometimes called these particles molecules. This may be explained partially by the pretest, in which it may have been mentioned that scientists currently think that everything is made up of

microscopic particles called atoms and molecules (Scott, 1992, p.210). However, some pupils had probably also learnt about the existence of molecules and atoms in other settings.

Drawings of a gas in one specific situation

The approach of Novick and Nussbaum initially focuses on the structure of a gas in one specific situation. After becoming familiar with the behaviour of gases, pupils are asked to imagine what air remaining in a closed flask may look like before and after part of it is pumped out. Again, as was to be expected, these pupils either did not spontaneously use particles in their explanations or came up with a model of tiny bits.

Meheut et al. also ask pupils to compose drawings of a gas in a specific situation, viz. before and after compression. However, in this approach an initial axiom is given, namely invariance of shape and dimensions of the constituting particles, which prevented pupils from giving macroscopic representations. Neither did they attribute changes of volume to the individual particles. However, we may doubt whether these pupils found this model worthwhile. It was, for instance, not attempted to make the aspect of invariance plausible to them.

A need for particle explanations because of a lack of (macroscopic) knowledge

In the approach of Séré, it is attempted to induce a need for a particle model. After explaining, in macroscopic terms, several phenomena of gases, pupils are challenged to explain two more experiments: a suction pad stuck to the wall and a piston of a closed syringe, filled with air, hanging still in spite of the weight attached to it. It was found (Séré, 1990) that the pupils could not agree on a suitable explanation and, furthermore, did not accept the macroscopic explanation of the teacher, who said that air, although not moving, was still pushing. So the children felt a need for an acceptable explanation. The model of invariant spheres that were always moving and colliding, which was introduced subsequently, provided them with the means to construct one. Permanent movement of particles became a part of explanations of several actions of air, especially when there was no macroscopic displacement.

Séré and Moppert (1989) have found that pupils did not often spontaneously use particles in their explanations, but were more willing to do so when they could not think of a satisfying macroscopic explanation. Séré (1990) also noted that some pupils who were quite satisfied with their own macroscopic explanations of the actions of air, did not accept the model that was introduced by the teacher. Both results seem to be negative consequences of the special way in which the model is introduced: the usefulness of the model is implicitly linked to the absence of a macroscopic explanation. Although we should probably not aim for a situation in which pupils spontaneously use a particle model all the time, it seems preferable that they find the model worthwhile even when a macroscopic explanation is known. In this sequence, the real value of the model seems to be all pupils understanding that air constantly produces actions, and moreover why this action depends on the quantity of air per unit of volume and on the temperature (Séré, 1990). However, we do need to ask whether this result could not have been reached without the introduction of a particle model. The authors argue that, before the model was introduced, the pupils did not accept the teacher's macroscopic explanation that air was pushing. But how much effort was made by the teacher to illustrate his explanation, and were the pupils sufficiently prepared by the previous lessons to understand that explanation?

From other results it seems that these pupils indeed lacked an adequate macroscopic basis. Only two out of ten children succeeded in taking into account every action upon a system,

for instance in the case that air acts on both sides of a membrane without any visible effect (Séré, 1992). This lack of adequate macroscopic knowledge has not been overcome by the introduction of the model, but simply reappears as the source of a distortion of this model: "The little balls always push, but not much! It's as if I pushed a building. It would not make any difference!" (Séré, 1990, p.58).
Furthermore, there were results indicating that some pupils considered the particles to be tiny bits of air. Séré and Moppert (1989) have reported that some pupils talked about "petites bulles" instead of "petites boules", which they believed indicated "une petite quantité d'air au niveau macroscopique" (p.12). According to the authors it is often ignored whether for pupils, air is composed of tiny bits of air identical to the macroscopic amount, or of little balls in empty space, or of little balls in air.

In the chemistry sequence of De Vos, molecules are also introduced when pupils realise that they cannot explain the outcomes of an experiment: when two white powders, together, are pounded in a mortar, a yellow powder emerges. Instead of introducing the whole model at once, pupils are only told that molecules cause this effect. According to the author this statement is accepted by pupils as a first step towards an explanation (De Vos, 1993). After molecules are introduced, pupils are told to assume that molecules of the same sort are identical: we call two objects identical when they differ only in position and movement, but do not show a difference in any other respect. And the creation of a new substance is "explained" as the creation of a new molecular sort.
It is interesting to see that the above assumption implicitly defines "the rules of the game": in future, all events in which the substances as such do not change will have to be explained solely in terms of changes in position and movement. This can be considered as an attempt, even though it is only an implicit one, to show pupils the specific way in which scientific particles are used. Unfortunately, it is not known whether this was recognised by the pupils. But, because of its implicit nature, and based on the outline, one can reasonably assume that it was not. For pupils did not possess any criteria to assess whether two substances were the same or not or whether a specific substance was indeed a chemical substance or a mixture, other than some secondary qualities, like taste or colour and maybe some common knowledge. Again, as was the case in the sequence of Séré, it seems that these pupils lacked an adequate macroscopic basis.

Differences between systems and constituting elements

In the sequence of Buck, pupils are first induced to think about the properties of systems and those of their components. When they realise that most systems possess specific qualities that are not shared by their components and vice versa, the topic of atoms is introduced via a set of nesting systems, represented by slides. The first slide shows a galaxy and it is explained that this is a system consisting of several components, such as our solar system. The next slide shows the solar system and the teacher argues that it consists of planets, such as our earth. This story is continued by showing that each time the component is itself a new system, until they arrive at a microscopic picture of a hair fibre. Considering the previous experiences, it is quite probable that this fibre consists of new components with different qualities. But there is no next slide: the components are no longer visible. Not because they are too small, but because they do not have the qualities that pupils know, such as colour and sharp edges. According to the author, this resulted in desperation: this step towards the atoms was quite a jump. And, he argued, a necessary one to understand the nature of the atom (Buck, 1987). Although these pupils probably had difficulties to imagine atoms without having properties like colour or sharp edges, at least it became quite clear that these particles differed from tiny bits. Unfortunately, Buck did not explain how his sequence deals with subsequent necessary steps. Presuming that atoms do not possess colour and sharp edges: what special properties should they have and why these?

The four different ways of introducing a particle model that were described above, can in turn be further classified in two distinct introductions, i.e. starting from tiny bits which are to be further developed towards the intended model in subsequent lessons, or attempting, from the start, to show some of the differences between both kinds of particles.

2.3.4 Further development of the model

The majority of the research based teaching sequences that were analysed do not present their educational particle model as a whole. Instead it is constructed step by step, either starting from pupils' ideas about particles or from an initial axiom, e.g. invariance of shape and volume (Meheut et al.) or molecules of the same sort are identical (De Vos). In this section we will examine how different aspects of classical scientific particle models are considered in the process of development.

Intrinsic motion

In all the analysed teaching materials that do not introduce the whole model at once, the aspect of motion of particles is first considered after the examination of a diffusion experiment (CLISP, Meheut et al., De Vos, Novick & Nussbaum). However, since there is macroscopic displacement in such experiments, they are easily explained by means of tiny bits and are therefore not very effective to make permanent motion plausible. The same holds for situations of dissolution and evaporation. We only need to assume that the substance divides into tiny bits, that these bits can travel from one place to another just like the macroscopic amount of substance can, and that these bits indeed do so when the substance does. There is no need to assume that these tiny bits also move when the macroscopic amount does not. Consequently, pupils' ideas about the nature of the particles, i.e. tiny bits, cannot really be changed by this experiment. Moreover, this argumentation even encourages pupils in their habit to explain all macroscopic change by means of a similar change at the particle level. Since some sequences (CLISP, 1987; Nussbaum, 1992) use such experiments to convince pupils to change their ideas anyway, intrinsic motion can only be forced upon these pupils and this probably leads to the real misconception that tiny bits always move. The reported results do not clearly demonstrate this kind of misconceptions. Johnston (1990), for instance, found that most pupils explained expansion of solids and liquids on heating in terms of particles moving further apart because of more vibration. She did not mention, however, how these ideas of vibration in a solid were brought forward in class, nor that this explanation could be found literally in the written summary that was probably handed out to them before they gave their explanations (cf. CLIS, 1987), nor what kind of particles these pupils were talking about. In other words: was intrinsic motion forced upon these pupils or not? Did their particles change essentially or did they think of tiny bits that not only moved faster but also became warmer, were coloured, etc. Johnston did mention that at least some pupils did not understand why the particles themselves did not expand, or, in their effort to explain expansion in terms of vibration, often struggled to express themselves clearly. This led her to conclude: "The fact that such [particulate] 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" (Johnston, 1990, p.262). It thus seems that the school science view did not immediately have to become worthwhile to pupils when new ideas like intrinsic motion were introduced.

Empty space between the particles

Some teaching materials attempt to induce pupils to understand the existence of empty space between the particles, either by considering thought-experiments and logical arguments (CLISP), or by explaining the compressibility of a gas (Novick & Nussbaum). In the sequence of CLISP, the following activities deal with empty space:

- a story or worksheet about a fish that died in pure distilled water;
- a worksheet which addresses the logical argument that there cannot be air between the particles of air;
- information from the teacher about the size of molecules, which are tremendously smaller than tiny bits.

The case study reported by Scott (1992) clearly showed that these activities were not sufficient in order to convince all pupils. The girl in this study, Sharron, used a model of tiny bits and believed that there were no gaps between the particles of solids, that there was air between the particles of liquids and that gases did not have parts. After the story of the fish, Sharron answered: "So, there might be some sort of gas. Em, I don't know what sort of gas... or just nothing" (Scott, 1992, p.216). As the author confirmed, she was obviously not convinced of empty space between the particles, which is quite understandable. The story may prove that there is no air between the particles of pure water, but it is still possible that the gaps are filled with some other gas.

After the teaching sequence, in response to what was between gas particles, Sharron wrote "pure air - nothing. Other - gases, muck, etc" (Scott, 1992, p.211). It thus seems that the logical argument had not convinced her either. Neither did the teacher's information about the size of the particles, for Sharron correctly remarked that the spaces between the particles still "must be fairly big for them to move about so" (p.217). In addition, she could have argued that they still did not need to be empty.

The author argued that it cannot be proven directly that there is nothing between the particles. "Ultimately, belief in the existence of nothingness in air demands an act of faith (a meta-physical commitment) which runs counter to everyday experience of continuous liquids and gases" (p.217). However, it may not just be a matter of faith. In this sequence, Sharron's particles may not have changed essentially. Although she decided that they were moving, they probably still were tiny bits of matter and then it must have seemed absurd to assume empty space between them.

The structure of the sequence of Novick & Nussbaum is quite similar. The main difference, compared to CLISP, is that because of the nature of their introduction of particle ideas (section 2.3.3) it may be considered a little more justified to assume empty space between the tiny bits. After having imagined how air in a closed flask may look before and after half of it is pumped out, pupils are asked to explain why air is compressible whereas water is not.

The authors have argued that, in every class, there was at least one pupil who suggested that air might always be made of little pieces with empty space in between. During the

subsequent discussion, more and more pupils joined the "particle camp" and were even willing to argue against their previous opinions (Novick & Nussbaum, 1981). According to the authors, "they personally felt the *need* for a theoretical model of the 'structure of air' which includes empty space in some way or another" (p.777).
However, the teacher probably also played a crucial part. Although refraining from explicitly expressing preference for any one drawing, the teacher pressed the "anti-particle" pupils to offer a better explanation of the air's compressibility and thereby implicitly told them that their models were not correct. Furthermore, this so called theoretical model probably still was a model of tiny bits, i.e. little pieces of air, and pupils were encouraged to believe that there is always empty space between these pieces.

Mutual interactions

The aspect of mutual attraction is hardly emphasised in any of the teaching materials that were analysed. If considered at all, it was either already assumed by the pupils or introduced in the explanation of cohesive properties of matter. When already assumed by pupils, they apparently found it plausible that the attraction was stronger between particles of a solid than between those of a liquid, which in turn was stronger than between those of a gas. However, it may actually be this strong connection with the states of matter which encourages pupils, for instance, to believe that the forces between particles change with temperature. The other form of interaction, namely mutual collisions, was either not considered at all, or hardly received any attention. In the latter case, the emphasis was much more on the collisions between the particles and macroscopic objects in order to explain the pressure of a gas.

2.3.5 The nature of particle models

The purpose of the model

In several approaches the purpose of the particle model remains rather vague (Novick & Nussbaum, Buck, Meheut et al.). In other cases it is connected to the way the model was introduced, i.e. the purpose is to explain macroscopic behaviour, sometimes mainly when a macroscopic explanation is not known. Some materials implicitly refer to a special way of explaining, e.g. those of De Vos, but none of the materials under consideration encouraged pupils to reflect on the specific way in which scientific particles are used in explanations. Therefore it cannot be expected that pupils who participated in these sequences learnt in what respect the educational particle model could really add to their understanding of phenomena, other than "being able to imagine particles everywhere". Nor that they learnt what a particle explanation consists in. In their view a particle explanation was probably either a description of what matter looked like from the inside, or at best a description of what happened to the particles in a specific situation.

The hypothetical nature of the model

When a model is introduced, it is often presented as a collection of facts. In the approach of Buck, for example, pupils probably found it quite understandable to assume that atoms did not have the same properties as macroscopic objects possess. But the point is that they were not asked to make such assumptions. Instead they were told, as being a fact, that these particles do not have properties such as colour. The same argumentation holds for the approach of Séré, in which pupils probably do not understand why some assumptions are made and, moreover, do not appreciate that these are indeed assumptions. This was more or less confirmed by Alex, a pupil participating in a case study (Séré, 1992). After he had learnt a second model, he stated that the first one "was not really true" (p.268). Although the sequence of Meheut et al. often refers to "representations", it remains unclear what is meant by this word and why exactly these axioms are given instead of others. Therefore, there is a considerable chance that pupils still interpret the model as a collection of facts. In other sequences, pupils are more involved in the construction of the model, which is derived from (thought-)experiments and logical arguments. However, a gradual development is by no means a guarantee that pupils will understand the nature of these models, since new elements can also be considered as facts when the reasons for introduction are not properly understood. In such cases, the process of checking hypotheses, investigating alternatives and following hidden consequences was not thoroughly dealt with and sometimes seemed to depend foremost on what was considered adequate by the teacher. Furthermore, since the purpose of the model was often not sufficiently clear, one may doubt whether pupils were at all in the position to judge and compare given hypotheses. In that respect, the attempts of CLISP to encourage pupils to reflect on such a process, by means of games such as a rule spotting game and a murder mystery, miss the point. It therefore is understandable that "many pupils had difficulty in making links between the games and scientific activities" (Johnston, 1990, p.251).

Thus, in spite of their own creativity and involvement during discussions, pupils may still develop the view that only one correct theory can be derived from the data, as a result of which the model may still be considered as a collection of facts. The extent to which it is certain that these particles exist, is not reflected upon in any of the approaches. At the most, it is not yet completely understood what these particles look like. Simply struggling to imagine such particles, however, is not identical to understanding the hypothetical nature of particle models.

The nature of the particles

In section 2.3.4 it was shown that once pupils use a model of tiny bits, it is not at all easy to encourage them to change these into another kind of particles. Furthermore, it was argued in sections 2.3.2 and 2.3.3 that even when the complete model, or at least some initial axioms, are given, this does not guarantee that pupils will not consider these particles to be tiny bits. Besides Buck, only De Vos explicitly asks pupils to reflect on differences between the two kinds of particles.

De Vos, for instance, uses the outcomes of experiments to prove that molecules are different from tiny bits. When pupils experience that after evaporation of salt water and subsequent condensation, the resulting drops of water do not taste salty, they are asked to consider what exactly evaporated: drops of salt water or molecules? However, from the outline of the sequence it can be expected that pupils are not able to assess whether salt water is a mixture of molecules or a mixture of tiny bits of salt and water. Therefore this question cannot really contribute to a better understanding of the differences. Their answer may well be "drops of water".

In another effort to show these differences it is argued that two white tiny bits do not unite to one yellow tiny bit, but only make a bigger white tiny bit. Since the two white substances, together, changed into a yellow substance, it is concluded that molecules are different from tiny bits. This indeed seems quite convincing. Furthermore, pupils are encouraged to imagine molecules as small machines: during the reaction each machine of the first substance unites with a machine of the second substance to form a new, more complicated machine which operates differently; by this different working the machine produces, for instance, a yellow colour when light shines on it. Thus molecules are described as small machines that move, attract each other and produce colours, smells and tastes. In addition, it is emphasised that an atom is not a small, massive ball but a rather complicated part of a molecule. One may argue that this way of explaining the nature of a molecule might not make much sense to pupils. Nevertheless, it is one of the few serious attempts to give pupils an idea of the differences between scientific particles and tiny bits.

The connection between the model and macroscopic variables

In order to test a particle model, it is not sufficient to specify what will happen to the particles in a specific situation. The reason is, of course, that one cannot directly observe what happens to the particles and, therefore, cannot directly test whether the microscopic behaviour is as predicted by the model. The only way we can test the model is by what we can directly observe, i.e., in essence, macroscopic phenomena. So what will have to be added to the model, as a way of giving empirical content to it, are its connections with macroscopic variables. From the teaching materials that were analysed, it appears that these connections are usually not considered to be problematic, for they only receive explicit attention in the approach of Meheut et al.

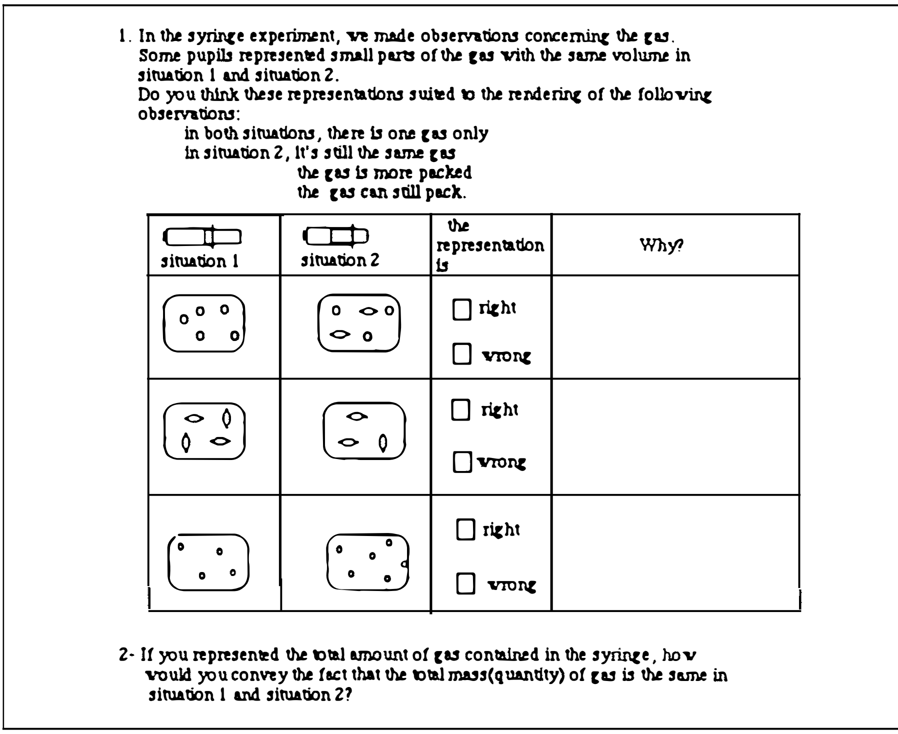
In this strategy, pupils are asked to discuss the compatibility of several representations or computer simulations with a previous description of a phenomenon (cf. fig.2.1). The representations incompatible with prior descriptions of the phenomena were properly understood as such by almost every pupil (Meheut & Chomat, 1990). But a large number (40%) argued only at the model level, without expressing the connections between the variables of the model and those descriptive of the macroscopic system. The sequence which incorporated computer simulations did not improve this result (Meheut, Chomat & Larcher, 1994). In other words, these connections were indeed established, but usually not explicitly mentioned.

Some of these connections are likely to be almost too obvious to express, e.g. between:
- the surface (dimensions) of frames and the volume of the samples of air;
- the number of particles and the quantity of air (Meheut, 1995).

Other connections may seem obvious at first sight, but are quite complicated on second thought, for instance the one between the weight of a gas and the sum of the weights of the particles. This, however, is not reflected upon. Another less obvious connection is the one between the temperature of a macroscopic amount of matter and the mean kinetic energy of the particles. This receives more attention, for example after the observation that diffusion proceeds at a faster rate at higher temperatures, or that the pressure of a gas increases during heating.

In addition, De Vos uses the idea that molecules of the same sort are identical, to explain why molecules of a heated substance have to move faster and why even molecules of solids have to move. Pupils are asked to consider two amounts of water, of which one is heated: since the molecules of the two amounts of water are of the same sort, they are supposed to be identical and therefore can only differ in position or movement. But, since a difference in position cannot account for a difference in temperature there has to be a difference in movement: molecules of heated water have to move faster.

This argumentation is an application of the implicit "rules of the game" as discussed in



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?

Figure 2.1 Expressing connections between the model and macroscopic variables (Meheut & Chomat, 1990, p.273).

section 2.3.3. In that section it was already doubted whether pupils would be able to completely understand this implicit definition. When they did not, they probably could not follow this argumentation either. Perhaps in their imagination particles could differ in temperature and still be identical. Furthermore, at first sight, a difference in movement can no more account for the observed temperature difference than a difference in position can.

Although in many sequences it is taught or decided that the mean speed of the particles increases with rising temperature, it does not become clear that the temperature of a macroscopic amount of matter does not correspond to the temperature of the particles. In fact, the latter connection seems very obvious, because it is similar to those mentioned above, i.e. those concerning the volume or the quantity of (samples of) air. Thus, pupils may well believe that hot particles move faster than cold particles (De Vos & Verdonk, 1987). As long as pupils do not understand that the mean kinetic energy of the particles, and *not* their temperature, corresponds to the temperature of the macroscopic sample of matter *in the same way* as the number of particles corresponds to the amount of this sample, further conceptual problems concerning the intrinsic motion of particles, such as reported in section 2.2, are likely to emerge.

2.4 Conclusions

The central problem presented in this thesis is tackled by designing and testing a new approach to teaching and learning an introductory particle model. This, however, immediately leads to the question of how to arrive at such a design. From analysis presented in the previous sections it is possible to further specify this question into five main problems, which will be discussed below.

In section 2.2, it was found that young children have difficulties to classify samples of matter as being either solids, liquids or gases. However, it was concluded that these problems might be of a different nature, than was suggested by several research articles. Instead of having incorrect ideas about properties of the three states of matter, it seems that young pupils have not yet sufficiently learnt to make a distinction between properties of materials and those of objects, as well as between substances and mixtures, in order to be able to make correct classifications. Furthermore, it was suggested that young children may know too little about the existence of invisible gases other than air, which makes it more difficult for them to describe specific changes of state. In other words, their knowledge of macroscopic phenomena is limited, but probably not incorrect. The above issues require more attention, and thus deserve more educational research.
Suppose that the above issues are indeed properly taught, then the question remains how pupils can be best assisted in the process of arriving at a particle model. The latter problem is quite difficult. In the previous analysis, it was argued that children mainly have experiences with particles that are the result of a process of division. These macroscopic particles were called "tiny bits", because many of their properties are the same as those of the macroscopic amount of substance from which they emerged. Interpretation of the reported ideas showed that when an educational particle model is taught, pupils probably assume that these particles are also tiny bits, which causes several conceptual problems. Pupils, for instance, attempt to change the assumptions of the model in such a way that they are more in agreement with the behaviour of tiny bits. Or they are not able to integrate the model into their previously developed knowledge, and instead learn the model by heart.
Thus, pupils' intuitive knowledge about tiny bits of matter is quite alright, but they should not be encouraged to call these particles "molecules". The latter is far from easy. Pupils should somehow come to feel a need to incorporate particles in their thinking, that differ from tiny bits. Séré and De Vos both attempted to induce such a need by starting from a lack of macroscopic knowledge. It was found that this lack of macroscopic knowledge can indeed induce a need for particles which are different from tiny bits. However, such an introduction also has considerable disadvantages, for there is a reasonable chance that problems that were not dealt with at the macroscopic level will keep interfering at the particle level. Eventually, such an approach is therefore not deemed to be effective. But, without a lack of macroscopic knowledge it seems even more difficult to induce a need for another kind of particles. When simply asked to give explanations of properties of the three states of matter, many pupils did not spontaneously come to feel such a need. The same may be expected for representations of a gas in specific situations. Instead, we have to find an aim, which pupils can come to find worthwhile, and which subsequently can be reached by means of particles that differ from tiny bits.

Problem 1:
Can we find an aim, which pupils can come to find worthwhile, and which creates a need for particles that differ from tiny bits?

Even if such a need can be induced, we cannot assume that pupils will subsequently spontaneously put forward a model that indeed differs from macroscopic particles. Furthermore, starting from a model of tiny bits does not appear to be the best option, for the analysis showed that, once pupils believed molecules or atoms to be tiny bits, it was very difficult to change these ideas. It therefore seems more appropriate to prevent the development of such ideas in the first place. In order to achieve this, it seems necessary to introduce specific elements of a scientific particle model, which pupils can hardly be expected to produce themselves. Not an excess however, for then the hypothetical nature of the model would be reduced, and in addition, pupils would have less opportunity to take an active part in the process of modelling. Examples of such specific elements which can be offered, include some of the previously described ways in which pupils are given an idea of the differences between molecules or atoms and tiny bits. For instance, the explicit invariance of shape and volume, the definition of "being identical", and the focus on differences between systems and elements. Yet, it is often quite difficult to make such initial axioms plausible.

Problem 2:
Which initial axiom(s) should be introduced and how can we make these seem plausible to pupils?

The analysis of research based teaching strategies for the introduction of particles showed that the model which is to be learnt in these approaches does not essentially differ from the one that is taught in general. The latter appears to be more or less a classical particle model, although some aspects do not receive sufficient attention, such as the nature of the particles and the correspondence between macroscopic properties and the model. Some of the research based teaching strategies seemed to omit even more aspects. We thus need to further discuss which aspects of classical particle models are important to teach and which specific model is essential for pupils to learn.

Problem 3:
Which model do we want pupils to learn?

Since we prefer pupils to participate in the development of the model, some aspects of the final model will have to be added to the initial axiom(s) at a later stage. Also, considerable attention will have to be paid to the way in which the model is connected to the macroscopic level. The way in which all of this can be accomplished very much depends on the way in which the above problems are solved. In this respect, the results of this chapter largely indicate that arriving at the correspondence between temperature and kinetic energy and at the aspects of intrinsic motion and empty space is quite difficult. Pupils somehow have to come to understand that the mean kinetic energy of the particles and not their temperature is connected to the temperature of the macroscopic sample of matter. Similarly, intrinsic motion is not an obvious hypothesis for the behaviour of particles of solids. Furthermore, it should not be introduced by means of a phenomenon that can be characterised as macroscopic displacement of matter, for such an introduction is exactly that which encourages pupils to assume that the particles are tiny bits that move when the macroscopic sample moves. In addition, it seems that the hypothesis of empty space between the particles can only be added when pupils already do consider these particles to be different from tiny bits. However, the way in which such hypotheses can indeed become worthwhile to pupils is still unclear.

Problem 4:
How can aspects that need to be added to the initial model become worthwhile to pupils?

Many of the reported ideas about the nature of science were interpreted as a naive view of science, which was considered to be caused by the stereotype information about science that is offered by various media. It is merely a vague image of what scientists do and achieve, and is mainly characterised by ignorance. It was argued that this naive view might become somewhat refined once pupils participate in science lessons. However, in such lessons, it seems that theory is often "derived" in a straightforward way from data and that models are usually presented as facts or simplified copies of reality. Therefore, it was argued that, because of the way in which science is usually taught, the naive view of science is mainly strengthened.

In many of the approaches that were analysed, pupils were actively involved in the development of the model. However, it was found that, in order to create a better image of the nature of particle models, such an approach in itself was not sufficient. The analysis showed that hardly any attention was paid to the purpose of the model and the special way in which particles are used in explanations. As a consequence, it is hardly possible to give pupils more responsibility in judging and choosing hypotheses. Instead, much input of the teacher is needed, which may result in ways of reasoning that are not convincing, or hard to follow.

Since we want pupils to learn about the hypothetical nature of such models, we foremost need to pay more attention to questions such as for which purpose and in which way the model can be used. Also, the process of checking hypotheses and investigating alternatives needs to be thoroughly dealt with. When the latter is not understood, pupils will be much more inclined to consider these hypotheses as a collection of facts. In addition, pupils need to reflect on the nature of the particles. More specifically, as a result of such reflections, they should come to understand that the particles differ from tiny bits. The analysis of research based teaching strategies has given few indications for the design of such an approach. It was mainly found that these issues should be taught in such a way that pupils clearly see the connection with the development of the model. Isolated activities, such as solving a murder mystery, do not seem to have the intended effect.

Problem 5:
How can we encourage pupils to reflect on issues that concern the "nature of particle models" in such a way that they themselves see the connection with the development of the model?

In the next chapter, a view on teaching and learning physics, as well as a view on particle models in physics education, will contribute to initial answers to the above questions. From that chapter, more specific questions concerning the design of our approach will emerge, that will, in turn, be answered by means of a more detailed account of the tested sequence.

3 Towards a solution

3.1 Introduction

In chapter 2, it was concluded that common teaching strategies about particles often result in misconceptions. Based upon their view on teaching and learning science, several researchers have attempted to develop a better approach for the introduction of a particle model in science education. However, they have not sufficiently succeeded, and five specific problems remain (cf. section 2.4). The way in which these problems are approached in this thesis is influenced by our own view on teaching and learning physics and, more specifically, particle models. In this chapter, the following question is answered:

> *Which view on teaching and learning physics and, more specifically, on particle models seems promising in light of our search for improvement of current teaching about particles, and which first steps can already be formulated in that direction?*

In section 3.2 and 3.3, our view is described, followed by a first general indication of how to solve the remaining problems in section 3.4.

3.2 View on teaching and learning

In this section, we elaborate on our own view on teaching and learning physics. Firstly, a few aspects of constructivism are discussed, as far as these concern teaching and learning, in order to illustrate how our own view builds on these ideas. After this view is further described, it is argued why, based upon our view, developmental research seems appropriate for our purposes.

3.2.1 Constructivism

As already discussed in section 1.2, for many topics, common teaching strategies show disappointing results concerning induced conceptual development. Consequently, a large number of attempts have been made to improve science education, many of which were based upon a so-called "constructivist view on teaching and learning". In the literature, this view is often connected to the philosophical constructivist movement, which deals with questions such as how knowledge, in general, is developed, and whether objective knowledge of a world "outside us" is at all possible. Such a discussion (Suchting, 1992; Matthews, 1994) may be quite interesting, but we believe that, for educational purposes, it is mostly irrelevant. In order to interpret our educational problem we confine ourselves to a few valuable ideas of "educational constructivism" (Ogborn, 1997).

Educational constructivism

In educational constructivism, learning seems to be viewed as a process in which the learner actively constructs new knowledge by interpreting new experiences and information on the basis of what he already knows (e.g. Driver et al., 1994; Matthews, 1994). Since it mostly remains unclear what exactly is meant by "actively construct", and since there are some indications that this view is debatable (see, for example, Piattelli-Palmarini (1980) for such a debate), we do not know to what extent this view on learning is appropriate. Therefore, we will not use this view on learning as such and, instead, use what we consider an important idea of educational constructivism in relation to improvement of teaching: pupils should be actively involved in the integration of new information into what they already know. Although this idea may be rather trivial, and in this general form most likely agreed upon by almost every educationalist, it appears to be not trivial at all to appropriately put it into practice. In much common education, for example, pupils are often rather passively listening to what the teacher explains. The educational constructivist idea that pupils should be actively involved in the integration of new information into existing knowledge, however, makes it understandable that such a traditional teaching strategy will often result in misconceptions: the knowledge that pupils already have, and the way in which this may influence their interpretation of new information, have probably not sufficiently been taken into account.

Educational constructivism is thus useful in order to interpret some educational problems, although it does not solve them. At a general level, it only gives a few valuable suggestions that may contribute to successful processes of teaching and learning, such as those that were summarised by Ogborn (1997):

- The importance of the pupils' active involvement in thinking if anything like understanding is to be reached.
- The importance of respect for the child and for the child's own ideas.
- That science consists of ideas created by human beings.
- That the design of teaching should give high priority to making sense to pupils, capitalising and using what they know and addressing difficulties that may arise from how they imagine things to be. (Ogborn 1997, p.131)

In order to actively involve pupils, constructivist strategies will have to provide pupils with relevant experiences, using social interaction as a necessary means to develop language and meaning (e.g. Edwards & Mercer, 1987), while at the same time these processes should be sufficiently structured to result in the intended conceptual development.

Constructivist teaching strategies

Guided by the educational constructivist idea, many different approaches have been developed, some of which were analysed in section 2.3. At a general level, two kinds of strategies can be distinguished. These have been classified by Scott et al. (1992) as based either upon "cognitive conflict and its resolution", or upon "the development of ideas that are consistent with the science point of view", i.e. the point of view that is aimed for in science education. Duit (1994) made a similar distinction, calling his categories "discontinuous" and "continuous pathways from students' conceptions towards science conceptions".

In strategies of the first kind, pupils' previously developed ideas about a certain phenomenon are made explicit and are challenged in order to create a state of cognitive conflict. Subsequent learning is then initiated by attempts to resolve this conflict. There appear to be mainly two ways to arouse such intended conflicts, namely either experiments are used in order to "show" pupils that their pre-existing ideas are incorrect, or several conflicting ideas about one issue are explicitly compared, one of which usually is the point of view that is aimed for by the designer. A well known example, which fits into this category, is the model for constructivist teaching sequences developed by the Children's Learning in Science Project (Driver & Oldham, 1986). This model comprises five phases: orientation, elicitation, restructuring, application and review. During the second phase, pupils' prior ideas are made explicit, and during the next phase pupils are exposed to conflict situations. According to the authors, as a result of such conflicts, "pupils may feel dissatisfied with their existing conceptions and hence open to change" (p.118). These expectations are based on theoretical notions about conceptual change that have been discussed by Posner et al. (1982). These authors argue that a new conception is unlikely to displace an old one unless the individual considers the latter with some dissatisfaction, and that anomalies are a major source of such dissatisfaction. In addition, they have pointed out that the anomalies need to be taken seriously by the learner in order to provide a cognitive conflict, and that the new conception needs to be intelligible, plausible and fruitful.

Teaching strategies of the other kind aim to develop those ideas that are consistent with the aims of science education. Duit (1994) distinguishes, in this respect, approaches in which specific aspects of these existing ideas are selected, namely those that are already largely in accord with the intended aims, from those in which well-known alternative ideas are reinterpreted. An example of the former is the use of "bridging analogies" (Clement, 1993). An example of reinterpretation is described by Duit:

> It is, for instance, a well-known students' alternative conception in basic electricity that the current is used up in the bulb so that less current flows back to the battery. (...) Instead of students' ideas being judged wrong they are told that their way of thinking is adequate in certain respects. In fact, there is something needed in order to let the bulb shine. But what is needed is not called current in physics but energy. (Duit, 1994, p.37)

Discussion

The success of the above strategies appears to be limited. In the previous chapter, the reasons for these limited results were already described at a content specific level, for instance in the case of the CLISP approach to the introduction of a particle model. This limited success may also be understood at a more general level. The emphasis of many of these strategies seems to be foremost on the translation of a supposedly necessary conceptual change process into a general teaching model. At a content specific level, such a general model however is not sufficiently detailed and therefore does not give enough indications of how to design successful specific teaching sequences.

More importantly, most of the above strategies seem to be based upon an inappropriate interpretation of pupils' previously developed knowledge. As was discussed in section 2.2, one should be quite careful in interpreting pupils' expressions, as there are several indications that pupils' beliefs are less in disagreement with scientific notions than is usually claimed. Thus, it becomes understandable why, in conflict strategies, pupils often do not experience the kind of conflict that was expected. Without such a conflict, discrepant events or critical tests cannot be convincing. But since it is assumed in conflict strategies that pupils' ideas are incorrect, the teacher needs to devaluate these ideas in some other way. This procedure further increases the likelihood that new knowledge is forced upon pupils, which, in turn, may enlarge the chance that real misconceptions are being developed. Strategies of the second kind do not attempt to devaluate pupils' previously developed knowledge, but these approaches nevertheless seem to assume that many of their ideas are incorrect (for specific elements that are not incorrect need to be selected), or in the case of reinterpretation, seem to read too much physics into pupils' statements, thereby still misinterpreting them.

Most of these constructivist teaching strategies thus assume that pupils have "alternative" ideas. This assumption may be correct when it concerns misconceptions that are developed as a result of education (e.g. combinations of "tiny bits" and taught aspects of scientific particle models, cf. section 2.2). However, concerning pupils' previously developed knowledge, before teaching and learning about a specific topic in science education has taken place, we believe that such an assumption is mostly incorrect (cf. Klaassen & Lijnse, 1996). Instead, we think it can be argued (Klaassen, 1995, p.9-20) that pupils' previously developed knowledge is largely correct or, as for instance in the case of particles, often hardly developed. The latter was also indicated by Scott:

> Sharron had not previously invested a great deal of thought in these matters. Any prior conceptions about the structure of matter did not exist in coherent, generalisable, 'theory-like' form (....) In other words, the alternative conceptions were developed after the start of teaching and it would therefore be wrong to characterise the learner's prior conceptions about matter in those terms. (Scott, 1992, p.220)

3.2.2 Our view on teaching and learning physics

A problem posing approach

The previous section showed that we adhere to a basic educational constructivist idea, but not to the alternative framework movement. We therefore will not make use of conceptual change strategies. Furthermore, although we believe that pupils' previously developed knowledge of specific topics is largely correct, the problem of how to design more successful processes of teaching and learning physics remains. In other words, it seems appropriate to make pupils actively involved in such a process, but how can we ensure that they are encouraged to integrate new information into their existing ideas in such a way that this does not result in misconceptions?

We therefore think it to be necessary to add another idea, which also sounds trivial, namely pupils should, at any time during the process of teaching and learning, see the point of what they are doing. If that is the case, pupils can more or less understand the purpose of each activity and assess why, in light of previous experiences, it is worthwhile to be involved in the activity. The process of teaching and learning, therefore, will then make sense to pupils. Such a situation is probably aimed for by many designers of teaching strategies, for we may expect that it will not only increase pupils' involvement, but also improve the quality of their understanding. If, at all times in this process, pupils see the point of their activities, it is expected that they will accept new knowledge on grounds that they understand. It is this second "trivial" idea that is the core of our problem posing approach. But even though this additional idea may also be trivial and agreed upon by almost everyone, it too appears difficult to appropriately put into practice.

When putting this idea into practice, the curriculum designer attempts to provide pupils with content related motives for the development of their knowledge. Thus, the emphasis is on bringing pupils in such a position that they themselves come to see the point of extending their knowledge in the direction intended by the designer. Klaassen identified two essential ingredients of a problem posing approach:

> The first is that pupils' process of science learning is, at any stage, provided with a local point, in the sense that their reasons for being involved in a particular activity are induced by preceding activities, while that particular activity in turn, together with its preceding activities, induces pupils' reasons for being involved in subsequent activities. The second ingredient is that their process of science learning is, at appropriate stages, provided with a global point, which is to induce a (more or less precise) outlook on the direction that the further process will take. (Klaassen, 1995, p.111)

In the attempt to provide pupils with both local and global motives for subsequent learning that Klaassen describes, problems play an important role. In brief outline, the designer thinks of some main problems and of some series of subproblems meeting the following conditions:
- the solution of each subproblem gives rise to the next subproblem in the series;
- subsequently solving the subproblems in a series eventually solves the main problem;
- and when the main problems are solved, finally, the educational goals intended by the designer are reached.

These problems and subproblems do not constitute the teaching materials, however. So they are not merely presented to pupils. Instead, the designer attempts to carefully devise activities in such a way that pupils themselves come to frame the problems and find them important, i.e., that they come to see the intended problems as their own problems. In addition, the activities need to be such that pupils can recognise how these may help in finding a solution and that by means of these activities they are indeed able to arrive at such a solution, while in the process they are extending their knowledge in the direction intended by the designer. Inducing problems in this way may be very difficult to achieve, especially with respect to the first main problems and subproblems. But if it is achieved, and if the designer is right in expecting that the pupils will be able to solve each subproblem, that the solution of one subproblem leads pupils to frame and find worth solving the next, etc., we think the result would indeed be a process during which pupils see the point of what they are doing and which eventually leads to the intended educational goals.
Although the above account is put in quite simple terms, it does bring out the tension between what Lijnse (1995) called "guidance from above" and "freedom from below": it is attempted to design teaching such that it guides pupils to develop "in freedom", i.e., in a process which makes sense to them, the very ideas that we want to teach. In addition, the account is rather idealistic. It cannot be expected that pupils will arrive at every solution wholly by themselves. The teacher and the teaching materials are supposed to guide the course of the learning process and, if necessary, introduce new concepts or information. Furthermore, it cannot be expected that all pupils will express all the problems of the outline themselves, but a problem posing approach does aim for a situation in which each problem is framed by at least some pupils and considered worthwhile to solve by all pupils. In particular, it needs to be clear to all pupils how a specific problem is related to previous experiences, why it appears worthwhile to solve it, and how the next activity will help them to do so.

Our view on physics education

The above two main ideas can be combined into a view on physics education. The educational constructivist idea more or less demands that pupils are allowed and encouraged to actively develop and integrate new physics contents into their existing ideas. The problem posing idea directs this process at a content specific level in such a way that this new physics knowledge is developed by their own reasoning and accepted on grounds that they understand.

An educational design that is based upon these two ideas thus involves pupils in a process during which they arrive at new knowledge as a result of their posing problems, framing and checking hypotheses, performing experiments, discussing the outcomes, and studying information that is offered. Since this knowledge is the result of their own reasoning, and established in discussions with each other and the teacher, pupils also implicitly gain some understanding of the hypothetical nature of this knowledge and of the way in which it was established. In other words, they implicitly come to appreciate that science consists of ideas about "what we find that nature can do" (Ogborn, 1997, p.128), which are created by people in a social process of framing, adjusting, weighing and rejecting hypotheses. In this sense, they can be seen as a community of researchers that generates physics knowledge in a similar way to that achieved in scientific communities, although of course much more controlled. It is therefore expected that such a process of teaching and learning will give pupils a better idea of the nature of science and, more specifically, of the way in which models can be used in physics. By making some problems worthwhile to solve for them and by encouraging them to develop and apply a model in order to solve these problems, pupils will not only experience themselves how models can be used, but also come to understand why specific hypotheses are framed and how these can be tested.

3.2.3 Developmental research

Designing such processes of teaching and learning is far from easy. In order to succeed, we have to put ourselves in the position of pupils, and from their perspective consider which problems, solutions, new problems, etc. will eventually lead towards the intended aims. We have to imagine which good reasons can stimulate which further development of knowledge and which activities can induce suitable motives in this respect.

In order to achieve this, extensive experience in designing challenging activities is not sufficient. Educational designers should not only be aware of pupils' prior ideas, but meanwhile need to consider how pupils will interpret subsequent experiences and information and whether they are able to understand why these are presented to them. In addition, activities should be designed in such a way that pupils can understand their purpose and find them worthwhile in light of their previous experiences.

Such a "bottom-up" approach requires extensive research, for the literature tells us too little about the subsequent steps of the learning process that pupils can and need to make. It is hardly informative concerning the questions that can initiate these steps, nor does it give sufficient directions for the way in which these problems can be induced and how pupils can be encouraged to arrive at the very knowledge that leads them towards a solution. Therefore, the tension between "guidance from above" and "freedom from below" can only be carefully regulated empirically (Lijnse, 1995). During the development of the approach it needs to be checked several times to what extent the intended and expected process really takes place and why it does or does not. This feedback of practical experience into the improvement of the approach induces a cyclic process of development and research. That is the heart of developmental research (Gravemeijer, 1994).

So, arriving at a problem posing approach by means of developmental research, initially involves selecting, as well as possible, appropriate subsequent steps in the process of teaching and learning and choosing or developing specific activities that may lead pupils to fulfill a specific motive and raise a new one. Subsequently, it is investigated whether pupils indeed raise the expected questions, whether they find next activities worthwhile in the light of these motives and whether they develop the knowledge that was aimed for. In other words, the thought-experiment in which the designer envisions the course of the process of teaching and learning, is subsequently tested (Freudenthal, 1991). To conduct such an investigation it is necessary to precisely express all the relevant expectations of what will happen during the process of teaching and learning prior to the investigation, and to compare these to the actual process that takes place. These expectations, a preliminary justification, and a description of the activities, together constitute a scenario.

> A scenario describes and justifies in considerable detail the learning tasks and their interrelations, and what actions the students and teacher are supposed and expect to perform: it can be seen as the description and theoretical justification of a hypothetical interrelated learning and teaching process. (Lijnse, 1995, p.196)

This scenario, on the one hand, serves as a means for the teacher to prepare the actual lessons and, on the other hand, is used by the researcher to test the chosen outline. Subsequently, the results of this test are informative for the further process of improving the design, which is then tested again. If subsequent results are not satisfying, a further cycle of improvement and testing can be performed. In the mean time, reflection on the results contributes to the development of theoretical notions concerning the teaching and learning of the specific topic. In the end, the scenario can be regarded as a rather detailed domain-specific theory for the teaching of this topic.
Arriving at this scenario initially demands small-scale qualitative research, with an emphasis on the development of educational knowledge at a content specific level. Firstly, it is investigated whether the intended process of teaching and learning can indeed be realised. Therefore, we consider an experimental design with one teacher, and one class for each trial, adequate and sufficient for our purposes. Subsequent research into the problems of implementation requires a design with more teachers. This, however, is beyond the scope of this thesis. Furthermore, the report of the research in this thesis will show an emphasis on the process of developing, testing, and improving the scenario. According to Freudenthal, it is that essential process that is often lacking in research reports.

> Researchers publish *products* of their activity, rather than the *processes* by which they were created; the knowledge of these processes is considered to be their private domain (...) This policy may (...) work in experimental sciences, where experiments, if satisfactorily described, can be reproduced by others more or less easily. In the social sciences, however, such a situation is quite exceptional. How, in any case, can one reproduce thought-experiments that have been kept secret? (...) Taking notice of the product, which allows for many interpretations, is not enough. In order to apply the product, one must also know how it came into being. (...) In short, developmental research means: experiencing the cyclic process of development and research so consciously, and reporting on it so candidly that it justifies itself, and that this experience can be transmitted to others to become like their own experience. (Freudenthal, 1991, p.160-161)

In other words, knowledge about how to teach a specific topic, has to be legitimised by the process by which this knowledge was gained, and it needs to be reported in such a detailed way that others can understand it. Since an important aspect of this process is the comparison of the thought-experiment to the actual course of the teaching experiment, both the scenario and the actual process of teaching and learning will be described at a very detailed level.

3.3 View on particle models in physics education

Particle models taught in secondary physics education are mostly of the following kind: a specific system is represented by a collection of entities and the behaviour of the system is explained in terms of the behaviour of the collection. These models are mostly a simplified version of classical particle models (as opposed to models of quantum physics) that are used in physics at university level. In this section, such classical particle models at university level are described. Based upon this description, it is then argued what kind of theoretical model we consider suitable for secondary physics education. Finally, it is discussed what kind of general motive pupils need to be provided with in a problem posing approach, in order to see the point of working with such a model.

Classical particle models

Examining several university physics textbooks, it seems that the classical particle models that are used have the following main characteristics. Such models are often used in order to come to a better understanding of why matter behaves in the way that it does. More specifically, they are used in order to explain macroscopic change solely in terms of changes in position and velocity of particles, that are due to mutual interactions. Coming to such a better understanding is only possible when hypotheses are framed about the constitution of the macroscopic system and about the behaviour of the particles. In addition, one also has to establish a correspondence between the model and the macroscopic system. More specifically, in classical particle models, it is assumed that a macroscopic system is a collection of invariant particles with specified masses, that move according to Newton's laws. Furthermore, the assumed mutual interactions are specified, in terms of microscopic laws, e.g. concerning the way in which the particles collide, in such a way that the behaviour of the collection of particles can be predicted. The system can then be represented by a point in the phase space of that system, and its evolution can be represented by a curve in the same space. The correspondence between the collection of particles and the macroscopic system is given by hypotheses that link the state of the collection to specific macroscopic properties. For example, the mean kinetic energy of the particles of the collection is linked to the temperature of the system. Such quantities can be expressed as functions on the phase space. These functions usually are of the type "many-to-one", e.g. there are a large number of microscopic configurations giving rise to the same value of the mean kinetic energy. Each classical particle model is thus specified by two kinds of hypotheses, namely concerning the mutual interactions, and the correspondence between the collection of particles and the macroscopic system. When such a model is tested, predictions about the behaviour of the system that are made by means of the model need to be compared to the actual evolution of the system. When the actual behaviour differs from the latter, there can be many causes, e.g. specific hypotheses about the interactions may be insufficient, or certain aspects about the assumed correspondence are perhaps inadequate. It goes without saying that improving the model is not a straightforward activity.

Finally, a specific model usually is only adequate in order to explain a certain collection of phenomena. Consider, for example, the following model:

a) a gas consists of identical molecules of mass m;

b) they have zero size, and do not collide with one another;

c) they exert no forces on one another;

d) their collisions with the walls of the container are perfectly elastic;
e) the pressure of the gas corresponds to the momentum transfer per second of all molecules on a specific area;
f) the temperature of the gas corresponds to the mean kinetic energy of the molecules.

Such a model can be used in order to explain several ideal gas laws. It can thus be called a model "of" an ideal gas. The model is not adequate to explain the behaviour of more dense gases. It can, however, be used as an example, or source of inspiration, in the design of a new model. In this way, the model "of" an ideal gas can serve as a model "for" designing a model "of" an imperfect gas.

A sufficient model for initial purposes

The model which pupils are expected to have developed at the end of our approach, within a sequence of about ten lessons, has to meet several demands. Firstly, this model clearly needs to have the main characteristics of classical particle models, in order to serve as a model "for" future modelling in physics lessons. Such characteristics are summarised in the framework of figure 3.1.

This framework seems useful to teach pupils what giving a particle explanation consists in. Filling in this scheme can illustrate how a macroscopic object is linked to a collection of invariant particles and that any change of this object is linked solely to a variation in position and movement of these particles, due to their interactions. It also clearly shows that there are two kinds of hypotheses involved in the use of particle models, namely those concerning the behaviour of the particles and those concerning the correspondence between the model and the macroscopic system. Concerning the further development of such models, the framework gives a fair idea of the boundaries within which hypotheses can be formulated and of the ways in which these can be evaluated. This framework can therefore be used

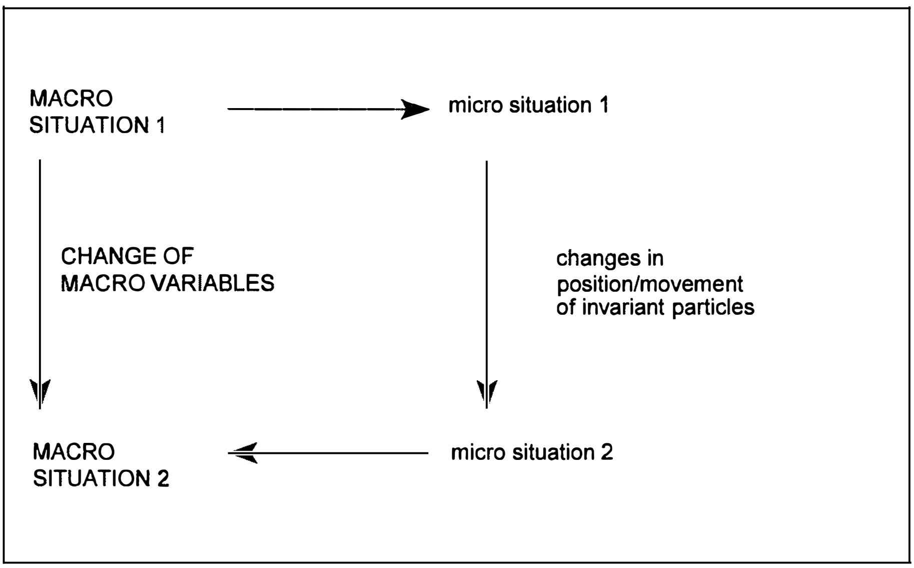


Figure 3.1 General framework of particle explanations.

as a means to teach about the hypothetical nature of particle models. Furthermore, if pupils come to appreciate that the particles of this model are invariant and only change in position and movement, these particles clearly differ from tiny bits.
Therefore, the model that is chosen as a final model in our approach needs to fit into this scheme. In addition, it needs to be sufficiently simple. Firstly, because pupils need to be able to imagine the behaviour of the particles in order to predict the final state of the system. Secondly, because they are supposed to partly develop the model themselves. The model that is chosen as a final model in this research therefore is more or less the same as which was summarised by De Vos and Verdonk (1996), minus the last two points of their list (cf. section 2.3.2), i.e. without the assumption that particles can behave as if they consist of one or more subentities. The particles of this model can thus be compared to what are commonly called "molecules" in secondary physics education, but with an additional emphasis on the above framework and on issues that, according to the analysis of chapter 2, are often not sufficiently dealt with.

Discussion

Given the fact that a model which more or less agrees with the list of De Vos and Verdonk is used in many traditional and innovative sequences, it can be assumed that many educators and teachers find this an acceptable version of scientific particle models. There is, however, also some criticism in the educational literature. Buck (1994 b), for instance, gave five reasons why, in his opinion, such a particle model is not appropriate to serve as an educational model. Three of these reasons concern the way in which matter is constituted, namely:

- particles do not have sharp boundaries;
- in some cases the model can not provide a good explanation;
- and the hardness of crystals is wrongly explained.

However, our aim is not to teach the latest scientific view on the structure of matter. Instead, we find it much more important that pupils learn what the purpose of a particle model can be, how one can arrive at specific hypotheses, within which framework these can be judged, what kind of experiences determine the extent to which one believes that these particles exist, etc. It is exactly by means of such a model as described above, that the hypothetical nature of particle models can be stressed, whereas the latest view on the structure of matter probably cannot. The latter is too difficult for pupils to participate in its development, resulting in ignorance of why specific assumptions were made, in turn leading to what Ten Voorde (1990) described as "textbookification", i.e. an excessive secrecy about the way in which scientists go about in getting their research results.
The fourth argument of Buck, namely on the pretension that there are only three states of matter, is important. It is expected that pupils' ideas about matter more or less agree with the naive theory of matter, which was summarised in section 2.2.4. This theory assumes that there are more than three physical states of matter. The expression "physical state" refers not only to the solid, liquid and gaseous state, but also to other manifestations of substances and mixtures, such as pastes and powders. However, often all kinds of materials that pupils encounter in everyday life, are excluded in educational strategies. Special properties of materials like rubber, lead, glas, clay, chocolate, milk, etc. are usually not studied in science education, nor is it explained that, in science, only specific materials are indeed classified as solids, liquids and gases. That is not to say that the model is inappropriate, but it is necessary to clarify that the collection of phenomena to which it is applied is limited. Therefore it appears preferable that pupils first learn to classify all

kinds of materials and to distinguish all kinds of macroscopic change, before they learn that some of these phenomena can be explained by means of a specific model.
Finally, Buck asserted that the model does not trust pupils to comprehend that these kind of particles on the one hand are the result of thinking processes while on the other hand we are barely able to imagine what they look like. In his opinion, the illustration of the model is its determining failure. In this respect, we agree that

> 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 water drops, 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 (Buck 1990, p.214)

can be very misleading. In addition, we would certainly not want pupils to think that matter consists of some sort of moving marbles. However, since we aim for pupils to give explanations and to further develop the model themselves, it is essential that they are able to predict the behaviour of the entities of the model. Without some kind of representation of these entities and their behaviour, it is almost impossible to construct kinetic explanations or predictions. Otherwise one would have to rely completely on heavy mathematics, which is too difficult for children.

Further development of this model within an educational context

The approach in this research does not cover other models that are usually taught in secondary school science. Nevertheless, the teaching of these subsequent models can greatly benefit from this initial learning. Having established the above framework, it will be possible to focus on similarities and dissimilarities between explanations that make use of molecules and those in which atoms, or nuclei and electrons, play a part. What changes between one model and another is what counts as invariant particles, e.g. atoms instead of molecules, and the nature of the mutual interactions, e.g. bonding forces in addition to vanderwaals forces. This consequently restricts and directs the possibilities for formulating new hypotheses: new explanations are found by considering new kinds of interactions, not by attributing properties such as colour or smell to the individual particles. When pupils, at some point, have good reasons to discard the assumption that certain particles, e.g. atoms, are invariant, in order to better account for specific macroscopic changes, the framework provides them with a motive to search for *new* particles that stay invariant during these changes, and for hypotheses concerning the interactions between those particles. As earlier, the degree of belief in the existence of the new particles grows with the amount of support that the new hypotheses receive from testing them, although of course, the testing itself may become more and more difficult.
The framework presented above does not clearly bring forward the many-to-one relation between the macroscopic and microscopic situations. That is, it does not clearly show that, given a specific correspondence between macroscopic and microscopic variables, there are still several possible states of the collection of particles that all correspond to the same macroscopic state. The question whether all, or at least many, of these states induce more or less the same behaviour of the macroscopic variables, consequently is also not dealt with. But it seems possible, by emphasizing the many-to-one relation, to raise this question, and thereby to relate the framework to statistical mechanics. We have not yet given this much thought, however, because it does not really seem necessary for our initial purposes.

It seems clear that particle models used in quantum mechanics do not fit in this classical framework. However, the latter does indeed prepare one for learning modern science. Firstly, quantum theories in science were developed when specific observations could no longer be explained by means of a classical particle model (e.g. atomic and molecular spectra) and when certain intra-theoretical problems seemed unsolvable within a classical model (e.g. the stability of an atom). Therefore, it seems that, especially within a problem posing approach, a classical framework can serve well as a preparation for learning about quantum physics: the above mentioned problems may indeed provide pupils with good reasons to adopt new nonclassical assumptions. In addition, it appears that essential parts of quantum physics can be better understood, given a secure classical background. For instance, the classical Hamiltonian has the same form as the quantum mechanical Hamiltonian, i.e. the sum of the kinetic and potential energy. And finally, an important aspect of working with models is to understand in which situations a specific model can be applied. Explicit comparison of classical and nonclassical models can enhance such an understanding.

An appropriate kind of global motive

A problem posing approach attempts to bring pupils in such a position that they see the point of extending their knowledge in a specific direction. At appropriate stages, they are therefore provided with a general motive ("global point") and, within each stage, suitable local motives for subsequent activities are raised. An important aspect of the educational problem presented in this thesis thus is which general motive can be provided, in the light of which pupils will come to find it worthwhile to consider a new kind of particles, namely that fit into the previously presented framework.

Across the entire secondary science curriculum, Klaassen (1995) makes a distinction between firstly practical and secondly theoretical, intentions and aims of pupils. When a practical orientation is induced, pupils' aims and intentions are directed towards the development of knowledge that can to some extent make people's lives more safe and/or comfortable. Problems that can be raised within such a practical orientation refer to situations in daily life. In the process of solving these problems, pupils develop their knowledge to an extent that is sufficient for these practical purposes. When a theoretical orientation is induced, pupils do not so much aim for an understanding of situations that are of practical interest, but rather want to search for a deeper understanding and further clarification of previously developed knowledge itself. Pupils may ask, for example, why established generalisations are as they are, or they may have noticed points where available ways of describing need to be improved.

The above distinction between practical and theoretical intentions/aims is not well-defined. Nevertheless, it appears worthwhile, because it will probably, at least initially, be easier to induce a practical orientation towards specific topics, than to bring pupils in such a position that they come to see the point of arriving at a deeper understanding of previously developed knowledge. From the perspective of long term curriculum development, it therefore seems sensible to initially provide pupils with general motives of a practical sort.

Having available this distinction, which kind of intentions and aims should be induced for the introduction and development of a particle model? That is, should an initial classical model be introduced in order to serve (a) practical or theoretical motive(s)? Even within an overall practical orientation, whether in physics at university level or in physics lessons at secondary education, particle models are used to improve understanding of known behaviour of matter. These models can thus become worthwhile to pupils when they see the point of arriving at a further clarification of previously established generalisations. Whereas previously these generalisations were used to describe how matter behaves in specific situations, it now becomes possible to explain why these laws, as such, are the way they are. In this sense, it seems appropriate to introduce a classical particle model as a means to solve problems that are raised within a theoretical orientation. It may, however, be quite difficult to induce such an orientation. Furthermore, it seems that pupils need to have developed a fair amount of macroscopic knowledge before it can become worthwhile to improve such knowledge. It therefore seems best to postpone the introduction of a particle model until later years of secondary education.

3.4 First steps towards improvement

Having described our view on teaching and learning physics and, more specifically, particle models, we will now use these ideas in order to come to a preliminary solution to the problems of section 2.4. These solutions, in turn, generate more specific problems concerning the design of the approach, which are dealt with in the next chapter.

Problems

The following problems were presented in section 2.4:

1. Can we find an aim, which pupils can come to find worthwhile, and which creates a need for particles that differ from tiny bits?
2. Which initial axiom(s) should be introduced and how can we make these seem plausible to pupils?
3. Which model do we want pupils to learn?
4. How can aspects that need to be added to the initial model become worthwhile to pupils?
5. How can we encourage pupils to reflect on issues that concern the "nature of particle models" in such a way that they themselves see the connection with the development of the model?

Basic ideas

The preliminary solutions are based upon the following general ideas about teaching and learning physics, as discussed previously.

* Pupils should be actively involved in the integration of new information into what they already know.
* Pupils' pre-educational knowledge about specific topics is assumed to be largely correct or hardly developed.
* At any time during the process of teaching and learning, pupils should be able to see the point of what they are doing. A problem posing approach attempts to arrive at such a situation by providing pupils with content specific general and local motives for subsequent learning.
* Within such an approach, pupils can be meaningfully involved in the modelling process, which in turn may contribute to their understanding of the nature of particle models.

Choices based upon our view

On the basis of the above ideas, choices are made which can be considered as first steps towards a solution to the above problems. These choices are discussed below, in a slightly different order: we start with a choice related to third problem, followed by a discussion of the second and first problem. Subsequently, the fourth and fifth problem are dealt with.
The third problem concerns an important aim of our approach: which model do we want pupils to learn? The model chosen as a final model in our approach agrees with the first six items of the list of De Vos and Verdonk (1996), with an additional emphasis on the invariant nature of particles and the correspondence between macroscopic and microscopic variables. The invariant nature is stressed in order to clearly distinguish the particles from tiny bits of matter. The correspondence is emphasised because these kind of hypotheses are an important part of particle explanations. By stressing these, in addition to hypotheses about the behaviour of the particles, the general framework of particle explanations (cf. section 3.3) will become more apparent, which in turn is considered important for future modelling activities of pupils.

The second problem concerns the initial axiom(s) that should be introduced and how these can be made plausible to pupils. Pupils may not find it obvious to include invariant particles in initial explanations. They may not even realise that, in specific situations, tiny bits do not lead to a satisfactory solution. To bring pupils in such a position that they do come to find the invariancy of the particles a worthwhile principle, it is important that an initial model, of which it is an implicit aspect that the particles themselves do not change, has already shown its value in solving specific problems. A model containing particles which are in constant motion, can serve as such an initial model, and already fits reasonably well in the framework.
Besides consisting of moving particles, the specific initial model should also be initially plausible to pupils. That means, firstly, that it needs to be intelligible: pupils should be able to imagine the behaviour of the particles and some connections between the model and macroscopic variables, in order to arrive at predictions or explanations. Secondly, in order to be initially plausible, the model has to have a prima facie fruitfulness. To this end, pupils need to be brought in a position in which it seems fruitful to give an explanation in terms of moving particles. The way in which pupils can be brought in such a situation is connected to our first problem, i.e. the problem of finding an aim, or general motive, which pupils can come to find worthwhile, and which creates a need for the model that is to be introduced. In section 3.3, it was argued that it seems appropriate to introduce a classical particle model as a means to solve problems that are raised within a theoretical orientation. An initial model, in which the particles are in constant motion, should therefore seem fruitful in order to come to a better understanding of previously established generalisations of behaviour of matter. So the question now becomes: in order to better understand which generalisations does a model of moving particles seem fruitful?
It seems that knowledge about the macroscopic behaviour of gases, and in particular pressure phenomena, may be a good candidate. Such a context may indeed provide pupils with good reasons to accept the introduction of permanently moving particles, as a possible means to further explain established generalisations concerning gas pressure. The acceptance of such a model is far more difficult to achieve when starting from knowledge about macroscopic behaviour of liquids and solids, or about diffusion and evaporation, i.e. macroscopic displacement. For it was argued in section 2.3.4 that such a context does not provide pupils

with good reasons to assume intrinsic motion, whereas gas pressure does. In summary, our preliminary solution to the first and second problem is to induce a theoretical orientation towards previously established generalisations of behaviour of gases and to introduce a sufficiently simple model of moving particles.

Let us now consider the fourth problem. In a problem posing approach, it is not only important that pupils consider the initial model worthwhile in the light of their intentions and aims, but also that they are provided with motives for hypotheses that are added during the process of modelling. As was discussed previously, intrinsic motion is expected to be initially plausible, in light of the induced aim to come to a better understanding of known behaviour of gases. Subsequently, the hypothesis that the particles are invariant may become more plausible when, amongst all explanations given, the particles themselves do not change. Once the latter assumption is accepted, the particles clearly differ from tiny bits. Then it will probably become easier to provide pupils with a motive to include the hypothesis of empty space between the particles.

So, within the orientation towards a better understanding of known behaviour of gases, it seems possible to make all the above assumptions plausible. The final model, however, also contains the hypothesis of mutual attraction. This additional hypothesis makes the model adequate, not only to explain known behaviour of gases, but also to explain phase transitions and some behaviour of liquids and solids. Since most of the other hypotheses need not be changed, the model "of" a gas could serve as a model "for" the construction of a model "of" gases, liquids and solids. Although one may expect that pupils will not find it very difficult to arrive at additional hypotheses, such as the assumption of an attractive force between particles, other conceptual problems may occur if the design is not sufficiently well thought-out. For instance, in the course of developing a model that also applies to specific behaviour of solids, the hypothesis of intrinsic motion may become less plausible. In a problem posing approach, therefore, pupils should eventually come to find it worthwhile to also come to a better understanding of previously established generalisations of known behaviour of liquids and solids, and to find it plausible to use a model of permanently moving particles to this end. It will be easier to induce this second general motive, the better the assumption of invariant particles is accepted: if the particles themselves are not allowed to change, all macroscopic changes have to be explained in terms of moving particles. Both in the development of the initial model towards invariant particles, and in the process of inducing a theoretical orientation towards a model of gases, liquids and solids, the correspondence between the temperature of a macroscopic system and the speed or kinetic energy of the particles can play an important part. Once it has become worthwhile to pupils to assume that the particles of a gas do not become warmer during macroscopic heating, but only come to move faster, this can make both invariant particles and movement of particles of solids more obvious.

In summary, our preliminary solution to the fourth problem is to spend an important part of the approach to the process of arriving at the correspondence between the temperature and the speed of the particles. It seems that after this hypothesis is established, it will be much easier to provide pupils with motives for additional assumptions.

Our final problem concerns reflection on issues that concern the nature of particle models. In chapter 2, it was concluded that teaching about the nature of particle models foremost consists in dealing with questions such as for which purpose, and in which way, such a model can be used. By inducing the intended theoretical orientation, initially towards a better understanding of known behaviour of gases and, at a later stage, also of liquids and solids, we automatically provide pupils with a purpose of the model. In addition, the framework that pupils implicitly develop when they are giving particle explanations (something like the framework presented in figure 3.1), should be made explicit. It can then serve as an important means to show pupils the way in which the model is used. It can illustrate that explanations are given in terms of invariant particles that only change in positions and movement, and that in order to give such explanations two kinds of hypotheses are needed. In particular, explicit attention for the hypothesis that the particles themselves do not change, will emphasise the nature of the particles, for it indicates that they differ from tiny bits. Furthermore, when the framework becomes more explicit, it can direct pupils' further modelling process, for new hypotheses need to fit into the established scheme. In this way, pupils can become aware of the boundaries within which the modelling process takes place.

In chapter 2, it was also argued that pupils will be more likely to consider the model as a collection of facts instead of hypotheses, when reasons for making these assumptions are not clear to them. In a problem posing approach, it is attempted to provide pupils with motives for extending their knowledge, so that they understand why specific hypotheses are made. In order to make the hypothetical nature of the model even more apparent, it is chosen to initially leave the existence of the particles implicit. While pupils are engaged in the development and application of the model, its increasing fruitfulness will probably influence their degree of belief in existence of the particles. At some point, this existence can then be explicitly discussed, which may encourage pupils to reflect on the way in which they have gathered information about the particles.

So, in order to encourage pupils to reflect on issues that concern the nature of particle models, we can emphasise the framework of particle explanations and existence of the particles. It seems that such an emphasis can only be achieved if, in some way or another, pupils can be made to reflect on what they have been doing so far. That means that we not only need to bring pupils in such a position that they arrive at good reasons to develop the intended model, but we also need to make it worthwhile for them to reflect on the nature of what they have developed. This seems to be an even more difficult task.

4 A problem posing approach to teaching and learning a classical particle model

4.1 Introduction

In chapter 3, an initial solution to the central problem faced in this thesis was discussed. This solution, as such, gives rise to subsequent questions, concerning a more detailed account of the way in which the intended process can indeed be realised. These are presented and dealt with in this subsequent chapter. From our initial answers to these questions we have constructed a scenario. This scenario has been tested and, based upon subsequent results, the initial answers have been modified. In this chapter, these modified answers are discussed and illustrated, by means of descriptions of specific activities and expectations of the course of the intended process. This discussion, as such, strongly resembles the improved version of the scenario that has been tested in the second trial, only the latter is still more detailed. The questions and answers are grouped into four related areas, namely:

- a theoretical orientation towards previously developed knowledge about behaviour of matter;
- the introduction of an initial particle model;
- the process of modelling;
- the nature of particle models.

These areas will be discussed in the subsequent sections of this chapter. The last area will also be considered in earlier sections, as it was argued that aspects of the nature of particle models should not be taught separately, but in close connection with other activities of the approach. Focussing on the four areas will occasionally force us to postpone our discussion of particular activities, or to jump to activities that are part of the end of the approach. Therefore, we start with an overview of the complete sequence:

Activity 1	A closer look at known regularities.
Activity 2	Framing a further question about the behaviour of air.
Activity 3	Introduction of the model.
Activity 4	Framing further questions about the behaviour of air and answering these by means of the model.
Activity 5	A summary of the answers: initial development of a framework.
Activity 6	An inventory of alternatives to account for Gay-Lussac's law.
Activity 7	Investigation of the alternatives.
Activity 8	Selection of the most appropriate assumption: adding to the framework.
Activity 9	Arriving at a mechanism for the explanation of conduction of heat.
Activity 10	Application of this mechanism in more difficult situations.
Activity 11	Reflection on the results: adding to the framework.
Activity 12	The value of the model developed so far.

Activity 13	Forming an opinion about the existence of the particles: the case of Brownian motion.
Activity 14	Evaluation.
Activity 15	Remaining questions concerning the particles themselves.
Activity 16	Investigations in order to answer the questions.
Activity 17	Reflection: additional hypotheses.
Activity 18	An outlook on a wider application of the model: liquids and solids.
Activity 19	Further development of the model.
Activity 20	Application and adjustments.
Activity 21	An inventory of adjusted models.
Activity 22	Comparison of the models.
Activity 23	An outlook on future developments.

4.2 A theoretical orientation towards previously developed knowledge about behaviour of matter

4.2.1 Introduction

The approach starts by inducing a theoretical orientation towards specific behaviour of gases, i.e. to bring pupils in such a position that they see the point of coming to a better understanding of gas laws (cf. section 3.4). Which knowledge should pupils already have developed, in order to make such an aim worthwhile to them? For which reasons would pupils initially agree only to consider gases? And in which way can a need for a further explanation of known behaviour of gases emerge? Which specific theoretical problems can be induced to this end? Section 4.2.2 will reveal how these issues were concluded in the scenario.

At a later stage in the intended process of teaching and learning, we want to induce a theoretical orientation towards a better understanding of previously established generalisations concerning the behaviour of liquids and solids. Which knowledge should pupils already have developed in order to also make this aim worthwhile? Which specific theoretical problems can be induced to this end? These questions will be answered in section 4.2.3.

4.2.2 Knowledge about macroscopic behaviour of gases

Knowledge and problems

Since it was decided to introduce the initial particle model as a means to come to a better understanding of behaviour of gases, we need to select which knowledge of such behaviour can serve as a good candidate for improved understanding. Considering our purposes, i.e. the introduction and further development of a *kinetic* model, the following gas laws were selected:

- when the amount of gas, in a specific volume at a specific temperature, is enlarged/diminished (n times), the pressure is increased/decreased (n times); (= a simplified version of Dalton's law);
- when the volume of a specific amount of gas, at a specific temperature, is enlarged/diminished (n times), the pressure is decreased/increased (n times); (= Boyle's law).

- when the (absolute) temperature of a specific amount of gas is raised (n times), either the pressure is increased (n times at a fixed volume) or the volume is increased (n times at a fixed pressure) or both change (= Gay-Lussac's law).

The first two laws were chosen because it is expected that, by means of a kinetic particle model, pupils can easily come to a better understanding of these laws. Apart from the correspondence between the pressure of the gas and the collisions of the particles on the walls, one only needs to establish connections that appear quite obvious, namely between:
- the number of particles and the amount of gas;
- the dimensions of the space in which the particles move and the volume of the sample of gas (cf. section 2.3.5).

In addition, the third gas law was selected to make it possible to deal with the less obvious correspondence between the temperature of a gas and the speed of the particles. The latter, in turn, is important in order to eventually make it plausible to pupils that the particles themselves do not change.
Concerning these gas laws, we aim to induce theoretical problems. These are more or less of the same kind, namely why is this specific gas law as it is? For instance, when the volume of a specific amount of gas, at a specific temperature, is enlarged/diminished (n times), why is it that the pressure decreases/increases (n times)? Besides these problems, other questions that ask for a better explanation of pressure phenomena may also become worthwhile, such as:
- why is it that a gas always fills up the entire available space?
- why is it that the pressure of a gas is always equally large in each direction?

Before pupils can come to establish the above laws, they need to have developed a fair amount of macroscopic knowledge about the behaviour of gases. In chapter 2, it was already pointed out that young pupils probably know little about the behaviour of air, and even less about other gases. Thus, pupils should first learn to consider an amount of gas as a material object. To do so, they need to understand that an amount of gas fills up the entire available space, that it has a mass, that it always exerts a pressure and that this pressure is equally large in each direction. In the process of teaching and learning these properties of gases, air could serve as an important example, but pupils should also become familiar with other gases, e.g. hydrogen gas, helium, oxygen, carbon dioxide, LPG and butane gas, and find out that the basic notions also apply to these. Furthermore, it should eventually become clear that the pressure which is exerted by an amount of gas, changes when the amount, volume or temperature of the gas is varied. Finally, the gas laws should be established as generalisations of the behaviour of all gases, provided that they are not too dense. In a problem posing approach, these issues should be dealt with in the course of solving previously induced problems. How exactly such a process of teaching and learning should best be designed, according to which specific questions, is not the issue of this research.[1] It is, however, assumed that pupils who participate in our problem posing approach to the introduction of a particle model have developed all the above understandings.

An attempt to induce a theoretical orientation

So far, it is discussed which problems, concerning which gas laws, should be induced. How can this be accomplished? The main issue, in this respect, is not so much how we can encourage pupils to pose these problems, but how we can bring pupils in such a position that they themselves come to find it worthwhile to solve them. Firstly, we attempt to appeal

to an intrinsic theoretical curiosity that several pupils may possess. These pupils may have already become interested in the origin of "everything" around them, how it all works and what it consists of. This can be described as a longing for some sort of deeper explanation. However, it is not expected that all pupils are driven by such curiosity. Therefore, it is attempted to show pupils that it can be worthwhile to ask why known generalisations are the way they are. To this end, we have chosen to focus on pupils' implicit knowledge about aims of physics, by means of reflection on some of their own previous results. In the first activity of the approach, by referring to these previous results, it is attempted to make pupils realise that in physics, knowledge of an ever more general kind is pursued. This more general knowledge may allow for understanding why previous (less general) regularities are as they are and, moreover, may be used to explain and predict more events in a better way. Subsequently, it may seem worthwhile to also attempt to come to a better understanding of why these more general regularities are as they are, because this will probably result in knowledge of an even more general kind by means of which even more can be achieved. The examples that are used to this end are not restricted to the behaviour of gases, but concern behaviour of liquids and solids as well. This will allow pupils to get an idea of how what they will learn about gases relates to other parts of their knowledge. Finding out why general regularities in the behaviour of gases are as they are, may then serve as an example of coming to a better understanding of all behaviour of matter. In other words, pupils may begin to appreciate that what they will learn about gases can also become useful when considering other phenomena, which in turn may make this new knowledge more worthwhile.
A disadvantage of this approach is that after this broad picture is given at the start, the choice to continue with the behaviour of gases, instead of other phenomena, cannot be motivated for pupils. More importantly, it is attempted to induce some kind of a need for knowledge of a more general kind, but not specifically for a particle model. In other words, a particle model can, in some sense, indeed be considered as knowledge of an even more general kind, but after the initial activities pupils will probably not expect that a particle model will be introduced. Thus, a theoretical orientation is not sufficiently induced. The latter is a more serious disadvantage, which will be further discussed after the following, more detailed description of the first activities of the approach.

Activities and expectations

The above attempt to raise a theoretical orientation is made in the following activities.
Activity 1 A closer look at known regularities.
Activity 2 Framing a further question about the behaviour of air.

The first activity focuses pupils' attention on what they already know about the behaviour of matter.

> The teacher puts forward some examples of regularities and asks pupils which ones they consider to be scientific regularities that concern the behaviour of matter. Of those that are selected, the teacher asks why these are as they are. For instance, why does a block of iron at room temperature always become warmer when you hold it in your hands? Based on their previously developed knowledge, it is expected that pupils will be able to answer by means of a more general regularity, for instance "when two objects are brought into contact, there will be a heat flow from the object with the initial higher temperature to the other until, in the end, the temperatures of both objects are equal." In addition, by referring to some examples, the teacher explains that such answers previously enabled them to explain many more phenomena and even predict new ones. By means of this reflection on their own previous experiences, it is expected that pupils will come to realise that it did prove to be worthwhile to come to a better understanding of

known regularities in the past. Finally, the teacher shows that even further questions can be asked in relation to these more general regularities, for instance "why, when two objects are brought into contact, will there always be a heat flow from..., etc." Instead of answering this new question, he explains that this is what they will be doing in the next activities, i.e. framing and answering further questions about known behaviour of matter, and that they will start with the behaviour of gases.

At the end of the first activity pupils probably have some, although rather vague, idea of what will happen during the next lessons, namely that they are going to find out why previously established general regularities in the behaviour of gases are as they are. They may also have some appreciation of the outcomes of this approach, namely some kind of even more general knowledge. Considering their previous experiences, they may expect this to be sufficiently worthwhile to continue, because this more general knowledge is likely to enable them to explain and predict even more phenomena. The second activity aims to further propel pupils in the intended direction.

The teacher asks what will happen to a closed plastic bag filled with air, when the surrounding air is being removed. All pupils are familiar with the experiment, so they should know that the plastic bag will become bigger. The teacher then explains that they know this because it always happens like that and asks them why a plastic bag, filled with air, always becomes bigger when the surrounding air is being removed. Since pupils already know how to explain this, they will probably answer that the air inside the bag wants to spread or that the air pressure outside becomes less than inside. The teacher subsequently explains that this is also a regularity: air always wants to spread out, or air always exerts a pressure. Again, he asks them why this is the case. Can they come to a better understanding of this? At this point, it is expected that pupils will become confused. They have probably never asked such a question before, and cannot answer it other than "that is just the way it is", "that is just a property of air", or "you just cannot further explain that". After some discussion, it is probably possible for the teacher to indicate, by referring to their own answers, that they cannot yet answer this question. And that one could, of course be satisfied with this result, but that they could also try to come to a better understanding by searching for an answer. He writes the question on the blackboard and explains that after the next activity they will continue to gather more questions like this one, of which they believe at first sight that it cannot (yet) be answered.

It is expected that concerning similar experiments, pupils are able to express other known general regularities in the behaviour of gases which cannot yet be further explained. In addition, we expect them to realise that the aim of the next activities is to pose problems that ask why such generalisations are as such, and to find solutions to these problems.

Discussion of the approach

Finding out why known generalisations are as they are, constitutes an aim that pupils themselves can understand, and by means of the first and second activity it is attempted to show them why this aim can be worthwhile. However, it should not be concluded that the problems as such are really pupils' own questions. That is, pupils do more or less frame these problems themselves, however one can doubt whether they are really challenged to find solutions, for they do not know how a search for answers should be conducted, nor do they have an idea of the kind of knowledge that they will arrive at. In the above activities, they may begin to suspect that the new knowledge which is to be developed will be of an even more general nature, but this in itself cannot direct their search. In other words, a real motive for the introduction of a specific particle model is still missing, and therefore initial activities cannot sufficiently induce a theoretical orientation. Consequently, it will also be difficult for pupils to estimate whether their search for answers will indeed lead to knowledge that can also become useful when considering other phenomena than the behaviour of gases.

During the first trial, after the initial activities (which were more or less the same as described above), pupils did pose several problems concerning known regularities in the behaviour of gases, but it indeed seemed that they were barely challenged to solve these problems. However, during subsequent revision of the scenario, we did not succeed in improving the approach in such a way that, before the model was introduced, pupils would already have a better idea of the kind of knowledge that they were to construct. Finally, it was decided to, at least, rearrange the activities in such a way that the initial model was offered much sooner, i.e. immediately after the second activity. In this way, pupils can begin to solve the first problem, i.e. why air always wants to spread out or why it always exerts a pressure, before they pose additional problems.
As a result of this rearrangement, the focus switched from "posing problems in order to find out why known generalisations are as they are" towards "posing problems in order to solve these by means of the introduced particle model". It can be expected that pupils' realisation of how the model allows such a problem to be solved will make it more interesting to pose, and solve, similar problems. This may especially be so if pupils indeed come to appreciate that the first use of the model brings them to a better understanding. Thus, in the second version, a theoretical orientation is raised to some extent but only after the introduction and initial application of the model in the third activity. Although, following this introduction, pupils will have an idea of how to solve subsequent problems, they probably still do not immediately recognise the model as being new knowledge about gases of an even more general nature (also cf. section 4.3.2).

4.2.3 Knowledge about heat and about behaviour of liquids and solids

Knowledge and problems

Before the model of gases can serve as a model "for" the development of a model of gases, liquids and solids, pupils should first come to find it worthwhile to assume that the particles will continue to move during and after any change of state. In chapter 3, it has already been argued that this may be achieved when pupils are provided with good reasons to assume that, during a temperature rise, the particles move increasingly faster, whereas the temperature of the particles themselves is not an issue.
Before such reasons can emerge, pupils have to have developed a fair amount of knowledge about heat transfer at the macroscopic level. In secondary physics education, the three main forms of heat transfer are commonly distinguished, i.e. conduction, convection and radiation. As a preparation for the introduction and development of a classical particle model, especially the first form is important. In the case of convection, there is a macroscopic displacement of matter, which, as was argued previously, cannot serve as an adequate context to learn about the intrinsic motion of particles (cf. chapter 2). In the case of radiation, heat transfer takes place without there having to be a macroscopic sample of matter between the source and the receiving object. Conduction, however, appears to be a very useful topic in this approach. Firstly, by means of a kinetic particle model, this form of heat flow can be easily explained in terms of transfer of momentum. Secondly, such a mechanism can well be used to describe several familiar examples of heating (leading to, for instance, changes of state), such as heating in an oven, on a hot plate or in hot water.
Before the introduction of a classical particle model, pupils should thus have established a sufficient idea of at least one aspect of heat transport, namely conduction. That is, pupils

should have arrived at the following generalisation: when two objects of different temperature are brought into contact, there will be a heat flow from the object with the initial higher temperature to the other until, in the end, the temperatures of both objects are equal.
Klaassen (1995) presented a sketch of an approach that may lead pupils to this generalisation. In summary this outline is as follows. First, pupils must come to see the point of an empirical study of what happens to the respective temperature of two objects that are brought into contact. Such a situation may be created when pupils, after a careful preparation, experience that:

- when object A feels warmer than object B, this does not always imply that A has a higher temperature than B (they may both be at room temperature);
- when they touch these objects there is a heat flow from their hands to these objects (or a cold flow from the objects to their hands);
- this flow results in a rise in temperature of both these objects which finally reach the same temperature (this rise happens faster for B than for A);
- by then A no longer feels warmer than B.

During a further study of the temperature of objects that are brought into contact, pupils may learn to use the expression "E is a heat flow from A to B", for the event of a simultaneous fall in temperature of A and rise in temperature of B, and eventually arrive at the above generalisation.

In order to modify a particle model in such a way that it can also be applied to solids and liquids, pupils need to have developed a fair amount of knowledge about macroscopic behaviour of solids and liquids during phenomena of heat transfer and changes of state. Fundamentally, they need to understand that substances can exist in three states, that there are characteristic differences between these states, and that substances themselves do not change during a change of state. This understanding presupposes a distinction between properties of objects and properties of materials, between substances and mixtures, as well as between properties of the same substance in three different states. The results of chapter 2 have indicated that, in traditional secondary physics education, these issues are probably not sufficiently dealt with.
The above distinctions may be developed by building on a specific type of common sense reasoning, namely that objects are usually distinguished on the basis of typical behaviour under typical circumstances. Science lessons should then aim to have pupils come to understand which forms of behaviour and which circumstances are relevant, according to science, in order to come to a hierarchical classification. The first distinction may be arrived at by discussing similarities and dissimilarities of, on the one hand, different objects that are made of the same material (e.g. an iron nail, an iron spring and iron filings) and, on the other hand, similar objects that are made of different materials (e.g. a block of clay, a block of wood and a block of iron). The second distinction may be initiated by learning how to make mixtures (e.g. solutions and suspensions) and how to separate substances (e.g. by filtration and distillation). This may then be followed by observation of, and reflection on, well known and less known changes of state. The latter should lead to the conclusion that some materials, namely substances, each have specific melting and boiling points, whereas others, namely mixtures, do not. In addition, pupils' attention may be focussed on properties of the same substance in three different states, and in particular on differences such as:

- liquids and solids are hardly compressible, whereas gases can easily be compressed;
- liquids and gases can easily change shape, whereas solids cannot;
- gases always fill up all the available space, whereas solids and liquids do not.

Again, this research does not investigate how pupils can be encouraged to arrive at the above understandings. Instead, we assume that pupils have somehow constructed this knowledge. Theoretical problems that may subsequently be raised, and also seem appropriate for the modification of an initial classical particle model, are for instance:

- why do these specific differences between solids, liquids and gases exist?
- why do substances eventually change state when they are heated or cooled?
- why does the temperature of a substance stay the same during a change of state, in spite of transport of heat?

A new theoretical orientation

During the approach, pupils should develop a theoretical orientation towards the above knowledge. Again, the main problem is not so much how pupils can be encouraged to ask the above questions, but how they can be brought in such a position that they themselves come to find it worthwhile to answer them. This is attempted in two ways.

Firstly, because of their experiences in the previous lessons, we expect that, when pupils arrive at activity 18 (cf. section 4.1), and probably even earlier, most pupils will assume that the model has more potential than its application to the behaviour of gases. Especially the established explanations of heat transfer (cf. section 4.4.2) and the discussion concerning the value of the model (cf. section 4.5.3), are likely to have induced ideas concerning a wider application and perhaps further development. So, even if the broad picture at the start of the approach did not yet sufficiently encourage pupils to assume that what they would learn about gases could also be useful when considering other phenomena, it is expected that they will arrive at the assumption during subsequent activities. In turn, arriving at that assumption will make the further process of modelling more worthwhile to them.

Secondly, the previous experiences are not only expected to have stimulated pupils to suppose the possibility of wider application and further development of the model, but also to have prepared them for exploring this supposition. On the one hand, the previous lessons should have provided pupils with the means to do so: asking further questions about existing knowledge of the behaviour of matter, answering these by using and, if necessary, adjusting the model, using indirect ways to gather new information, etc. On the other hand, general knowledge about particle models, which was developed during the reflective activities (cf. section 4.5.2), is expected to serve as some sort of guideline for this exploration. In particular, it is expected that they will continue to assume that the particles themselves do not change. As a consequence, they will search for new assumptions about the interactions between particles, in order to account for new changes on the macroscopic level.

Discussion of the approach

Compared to the start of the approach, pupils are now provided with a motive for the use of a model that is much more content related. Posing and answering further questions, is motivated by their urge to find out whether and how the model, which they are familiar with (as opposed to their situation at the beginning), needs to be adjusted in order to also come to a better understanding of the behaviour of solids and liquids. The remaining question is how long pupils will find it worthwhile to continue this subsequent process. They may be satisfied at an early stage, i.e. before they have sufficiently thought through whether the adjustments are indeed adequate. In that case, they will probably not raise further questions. This will be further discussed in section 4.4.4.

4.3 The introduction of a particle model

4.3.1 Introduction

In section 3.4, it was argued that the initial model offered to pupils, should be sufficiently intelligible to them, and should leave pupils possibilities in becoming engaged in its subsequent development. Furthermore, the particles of this model should move. This leads to several further questions. Which specific model meets these requirements? How can it be introduced in such a way that it is indeed intelligible and can be used by pupils themselves to find answers to the questions that they raise? And how can we ensure that, at least in the beginning, it remains uncertain whether these particles exist, whereas in the meantime it does become worthwhile to pupils to use this model?

In section 4.3.2, it will be discussed which model appears suitable to be offered to pupils in this approach, and section 4.3.3 will give an account of the way in which this model is introduced.

4.3.2 A suitable initial model

In the search for an adequate model, an analysis of the role of classical particle models in the history of science can be quite helpful. Not only because these models are likely to be less complicated than contemporary ones, but also because the use of a model constructed by a scientist in the past can make pupils' own modelling process seem more important to them (cf. section 4.3.3).

In the past, many particle models were constructed for various purposes. A very ancient model, which is often referred to in science educational literature, is that of Democritus. Although the particles of this model were assumed to be invariant, and changes of macroscopic objects were explained in terms of movements of these particles, this model does not meet our requirements. It foremost seems to have been a rather philosophical model, with much emphasis on the connection between the variability of the world and the immutability of being, and which was used to explain the whole world including the human soul and the gods, instead of specific natural phenomena (Dijksterhuis, 1961). Similarly, the models of Descartes and Gassend are not adequate for our purposes. Although the particles in these models only possessed geometrical-mechanical characteristics, they remain too vague in order to be tested.

> Everything remains in the vaguely qualitative sphere, so that there is no question of an experimental verification of the truth of theories in question. On the ground of a curious kind of corpuscular imagination, explanatory hypotheses are formulated which may be considered more or less plausible, but which cannot be verified in any way. (Dijksterhuis, 1961, p.430)

Other models were especially constructed in order to explain pressure phenomena, such as the spring model of Boyle or the repulsion model of Newton (Brush, 1965), but the particles in these do not move. The first kinetic model that was constructed in order to better understand generalisations such as those mentioned in section 4.2.2, is the model of Leonhard Euler.

> Euler conceived the air as whirling spherical molecules closely packed together. Upon a spherical core of aether fits a shell of the "true substance of air", covered in turn by a shell of water. Air pressure is a manifestation of the centrifugal force which accompanies the whirling. (...) Assuming that at any given temperature the linear speed v of the vortex motion is the same for all the air and water particles, Euler derived an equation of state (...). For dry air which is not too dense he obtained as an approximation $p \approx \frac{1}{3}\rho v^2$. (Truesdell, 1975, p.3)

This derivation was rather complicated and, moreover, it seems that the model is too difficult for pupils to understand. One that is much easier to comprehend, was developed soon afterwards by Daniel Bernoulli. He assumed that air consisted of spherical particles that performed translational motions in all directions. Pressure was understood as a consequence of the collisions of these spherical particles against the wall of the container. In addition, he derived Boyle's law mathematically: when the volume of an amount of gas is increased by s ($s < 1$), then the pressure is increased from P to π, where

$$\pi = P\,[1 - \sqrt[3]{m}]/[s - \sqrt[3]{ms^2}] \,,$$

with m being the value of s at the smallest possible volume of the gas, i.e. when all the particles touch each other. When $m = 0$, Boyle's law follows, for then $\pi = P/s$ (Hooykaas, 1971; Brush, 1965). Such a derivation cannot be expected from pupils in secondary education, but Bernoulli's own qualitative argumentation is far less difficult:

> Now when the piston [is moved in such a way that the volume of the gas decreases], it is subjected to a greater force by the fluid in two ways: first because the number of particles is now greater in proportion to the smaller space in which they are confined, and secondly because any given particle makes more frequent impacts. (Brush, 1965, p.59)

At the time, this model did not receive the attention it deserved, because it was neither Cartesian nor Newtonian (Hooykaas, 1971). However, for educational purposes it seems a very appropriate model[2] to introduce, for it is essentially the same as the more advanced classical models that were developed in the nineteenth century, that is, showing an emphasis on the movements of the particles. It further has the advantage of still being relatively simple, which means that it can be further developed in the process of giving particle explanations. In addition, this model may be sufficiently intelligible to pupils, in particular because the particles have dimensions (although these need to be diminished to zero in order to actually derive Boyle's law quantitatively). This is expected to be easier to comprehend than, for instance, point masses (cf. the model described in section 3.4).

4.3.3 The introduction of the model

Initial acceptance

The model of Bernoulli can become even easier for pupils to comprehend when it is clearly illustrated. Therefore it was chosen to present the model by means of a computer simulation (cf. appendix B), which displays images of the way in which the particles move and collide. Furthermore, the introduction needs to be such that the existence of the particles remains quite uncertain, while this should not prevent pupils from an initial acceptance of the model. According to Van Hoeve-Brouwer (1996) this acceptance is an important issue.

> ...the first step must be to *accept* the idea of subsystems of substances. The second step is to *use* these subsystems in describing and explaining the behaviour of substances in a theoretical framework. (Van Hoeve-Brouwer, 1996, p.48)

However, the acceptance of the hypothesis that matter has a corpuscular structure may largely depend on the usefulness of a specific particle model. In our approach, the process of accepting the corpuscular hypothesis is intertwined with the process of coming to value the introduced model as a means to further explain already established generalisations. Therefore, the model is offered by means of an analogy: the teacher suggests that in specific situations, namely those of pressure phenomena, the behaviour of gases seems to be similar to the behaviour of a collection of "little balls" that move and collide, and that, therefore, gases are perhaps "something like" such a collection. This special introduction is expected to have several benefits. For instance, a comparison between "something new" and "something that is easier to understand and better known" can serve as a source of inspiration in order to arrive at an explanation, and as such is often used in physics. Assuming that pupils have used some sort of analogy in previous physics lessons, the teacher can remind them that this strategy was successful in the past. This may make the model more worthwhile to them.

Furthermore, in the case of the analogy, as compared to the suggestion that a gas might really consist of such particles, doubts about the existence of these "little balls" are, at least initially, less important. As in the latter case, it is already assumed that these particles exist, whereas in the first case it is only assumed that a gas behaves in the same way as a collection of such little balls. Pupils may thus be more willing to accept this suggestion to compare the behaviour of gases to the behaviour of a collection of "little balls", than to agree to the idea that a gas might really consist of such strange, i.e. moving and spherical, particles. After having noticed that, in a rich variety of situations, gases behave just like a collection of moving and colliding balls, the difference between the analogy that a gas behaves like such a collection, and the hypothesis that a gas really consists of such particles, is likely to gradually disappear.

Because it is not assumed from the beginning that a gas really consists of these particles, pupils may be less tempted to assume that these little balls are "tiny bits", since it is not clear whether these are really tiny bits of the gas. And, finally, although the model may trigger previously developed ideas about molecules or atoms, the absence of the latter terms and the large degree of uncertainty probably minimise these kind of associations. In this way, pupils obtain a better opportunity to become creative in the process of modelling, whereas possibly useful knowledge about molecules or atoms can still be used productively by individual pupils. However, since the connection between the model and existing ideas about molecules or atoms is not stressed, there is a chance that some pupils find the above comparison absurd. It is important that these pupils receive the opportunity to explain their objections and to discuss these with other pupils. Otherwise it will become quite difficult to encourage them to use the model.

Activities and expectations

The above introduction of the model, and its subsequent initial application, take place in the third and fourth activity.

Activity 3 Introduction of the model.

Activity 4 Framing further questions about the behaviour of air and answering these by means of the model.

The model is introduced after the teacher raises a question about a known regularity in the behaviour of gases, namely why air always wants to spread out, or why air always exerts a pressure (cf. activity 2).

The teacher explains that, in order to come to a deeper understanding of known regularities, it can be useful to compare this behaviour to the behaviour of something that they already understand more deeply. He reminds the pupils that they have done this before, namely when they compared the behaviour of air to the behaviour of water in order to understand why the pressure of air is smaller at a larger distance from the surface of the earth. It is expected that pupils remember that this comparison was very useful at the time. The teacher then suggests the new comparison, shows the computer simulation and meanwhile tells a short story about Bernoulli. Subsequently, pupils are asked to respond to the suggestion. Some of them may put forward that one does not know whether air may be compared to such a collection of balls, or whether air is indeed such a collection. Other pupils may defend the model and put forward that air was not the same as water either, while that comparison still turned out to be worthwhile, and that may also be the case now. If pupils do not think of this themselves, the teacher can explain it to them. In addition, he indicates that in order for this new comparison to be worthwhile too, they should find out whether in this case both behave in the same way.

It is expected that pupils are willing to temporarily set aside their objections, because they are taken seriously and because the model is still being investigated instead of accepted. As the presented model is rather simple, it will probably not be very difficult for pupils to see how the first question that was raised can be answered. Their answers may be similar to the following:

Question: why does air always want to spread out?
Answer (in this case air behaves just like a collection of bouncing balls): because they are moving and colliding, the balls move away from each other when they are no longer resisted by their surroundings.

Or:

Question: why does air always exerts a pressure?
Answer (in this case air behaves just like a collection of bouncing balls): because they are moving and colliding, the balls collide against objects around them and thus exert a force on each area.

These answers bring pupils closer to a better understanding of the behaviour of air. Of course, only to some extent, since they are unlikely to believe that air is actually a collection of colliding balls. Because of this deeper understanding, they may begin to suspect that the model may be a useful tool in order to come to a better understanding of other generalisations. This, to some extent, may make it worthwhile for pupils to continue to use the model, and thus motivates the fourth activity (also cf. section 4.2.2). In this activity, pupils pose and answer further questions about other known generalisations of the behaviour of air, including the selected gas laws. The previous activities are expected to have prepared them in such a way that they now understand what kind of questions and answers can lead to a deeper understanding.
The activity is guided by a worksheet (cf. appendix A). All pupils reflect on the same generalisations, in order to ensure that the collection of questions and answers will not become too large. The selected phenomena meet the following demands:

- All pupils are familiar with the phenomena, i.e. all pupils will agree about what happens in each case and are able to understand why. Their explanations will involve the generalisations that were selected in section 4.2.2;
- Provided that they all possess the required previous knowledge, they are in reasonable

agreement about the question that can be posed in each of these cases.
- The answers to these questions are likely to implicitly represent the intended connections between model variables and properties of the macroscopic amount of air, except for the last one, which concerns Gay-Lussac's Law.

Pupils' questions and answers are likely to be similar to the following:

1. Why does air exert a pressure in all directions? / Why is air strong enough to resist things that have a higher density (at least to some extent)?
   The balls move in all directions and therefore collide, in all directions, against other objects. / The balls move so fast that their impact is large enough to balance the gravity of these objects.
2. Why is the pressure proportional to the amount of air in a specific container (with fixed volume and temperature)? / Why does the pressure always increase when more air is pumped into such a container?
   When there are more balls in the same space, then more balls will collide against the walls of the container and thus exert a greater force on each area.
3. Why is the pressure inversely proportional to the volume of an amount of air (at a constant temperature)? / Why is Boyle's law as it is?
   When the volume of the space in which these balls are moving, is decreased, each ball will travel a shorter distance before colliding again, and thus will collide more often.
4. Why is the pressure proportional to the temperature of an amount of air (with a fixed volume)? /Why is Gay-Lussac's law as it is?
   (There can be several answers to this question, cf. section 4.4.2.)

Some groups may answer their questions without explicitly mentioning the collisions of the balls, for instance by saying "more balls in a fixed container results in more pressure." It is expected, however, that they will be able to explain this intuitive statement by means of a more detailed mechanism. The teacher should therefore encourage this. During the fifth activity, the answers are summarised by the teacher in an initial framework. This will be elaborated in section 4.5.2.

Discussion of the approach

It needs to be stressed again, that a real motive for the introduction of the model is missing. Instead, its introduction is based upon the successfulness of previous comparisons. However, the successfulness of the comparison between for instance air and water, as such, cannot really be a motive to compare air to a collection of balls, for it is not clear to pupils why they should not compare the behaviour of air to the behaviour of yet something else. That is why we may expect that some pupils will initially object to the comparison. What is a convincing reason for choosing exactly this comparison does not emerge until after the suggestion is made, namely its immediate success. Although it may well be expected that this success, in turn, will indeed make pupils more interested in coming to a better understanding of other gas laws, the motive is not as strong as desired.

4.4 The process of modelling

4.4.1 Introduction

Besides the problem of selecting adequate previously developed knowledge and of the introduction and acceptance of an initial model, several questions can be framed concerning the process of modelling. Such questions may concern:

- the correspondence between the collection of particles and the macroscopic system (discussed in section 4.4.2);
- hypotheses about the behaviour of the particles (section 4.4.3);
- the way in which the model "of" a gas is used by pupils as a model "for" designing a model "of" gases, liquids and solids (section 4.4.4).

4.4.2 Linking the collection of particles to the macroscopic system

Initial implicit connections between macroscopic and model variables

As soon as pupils start to apply the initial model, they implicitly establish a correspondence between macroscopic and model variables. Considering the expected course of the above activities, we may expect the following connections.

macroscopic variable	is linked to	*model variable*
PRESSURE		the total force per area that the particles exert by means of their collisions
AMOUNT OF SUBSTANCE		the number of particles
VOLUME		the space in which the particles move

These connections between macroscopic and model variables are rather obvious and it is therefore highly probable that, when working with this model, pupils will also intuitively establish these relations. In other words, they do not need any additional reasons to do so. The next connection that needs to be established is the one between macroscopic temperature and the speed of the particles. This one is expected to be more difficult, and therefore receives more attention.

Connecting temperature to the speed of the particles

In section 3.4, it was suggested that, in the process of arriving at the basic assumption that the particles themselves do not change, the correspondence between the temperature of a gas and the speed of the particles could be important. How can pupils arrive at the latter hypothesis? How can pupils be provided with good reasons to explain heating by means of a mechanism involving faster moving, instead of changing, particles? And which specific knowledge do pupils already need to have developed in order to be capable of imagining such a mechanism?

The question why Gay-Lussac's law is as it is, asks for a new mechanism that can explain why the pressure of a fixed amount of gas, in a fixed volume, increases when the temperature is raised, i.e. why the total force exerted by means of collisions increases during that event. In comparison to the other connections, that are expected to be intuitively established by pupils when using the model and which are made explicit in activity 5 (cf. section 4.5.2), it seems natural to assume that the temperature of an amount of air corresponds to the temperature, or perhaps mean temperature, of the individual balls. However, such a correspondence is not sufficient to answer the question, for balls that are only warmer do not collide with a greater impact, nor more often. Thus, irrespective of whether the balls do or do not become warmer in the event of heating a gas, a change of another variable is required in order to account for the larger force exerted by means of collisions.

Bernoulli assumed that in the event of heating, the speed of the particles increases. Then the rate of collisions as well as their impact will increase. Taking the invariancy of the particles as an initial axiom, there seems to be no alternative than to agree with Bernoulli. When, however, such an axiom is not yet considered as worthwhile, there are also other possibilities: not just an increase of the speed amounts to a higher pressure, but also an increase of the volume of the particles (because it increases the rate of the collisions), or an increase in their mass (because this raises the impact of the collisions).

In the process of coming to see the point of assuming invariant particles, the educational challenge is to provide pupils with good reasons to choose the assumption of Bernoulli in favour of the other two options (and perhaps still other ones). One reason may be that the mass of an amount of air is not increased in the event of heating, which suggests that neither is the mass of the particles. To argue why the volume of the particles does not increase in the event of heating, is more difficult. Since the mass of the particles does not increase, it appears less obvious that their volume does, although it is possible. Assuming that the distances between the balls are much larger than their dimensions, a larger volume of the balls would only lead to a very small increase of the pressure, as compared to the effect of faster moving balls, and therefore the latter hypothesis appears more likely. Moreover, in order to account for a considerable increase of pressure, the volume of the balls would have to become very large, which, in one way or another, should become perceptible at extreme heating, whereas such a phenomenon is not observed. Although the reasoning against larger dimensions of the balls is less convincing than the rejection of a larger mass, it is expected that, in comparison to the hypothesis of a larger speed, pupils will reject both in favour of the latter.

This part of the approach, even more than the previous parts, requires pupils to be able to derive, from the behaviour of a gas, new hypotheses about particles. The earlier process of coming to understand the behaviour of air at a macroscopic level, may in fact also prepare pupils for this special way of working with a particle model (Genseberger, 1994). Deriving knowledge about invisible air from results of experiments, is in a way very similar to the indirect way of gathering knowledge about particles: in both cases one has to form an idea of something which cannot be seen, by means of an analysis of its effects.

Activities and expectations

In the first tested version of the scenario, pupils were offered a worksheet in which the intended answer to the question concerning Gay-Lussac's law, was more or less suggested to pupils while alternative hypotheses were not considered. Although initially pupils did not object to assuming that the speed of the balls would increase during heating, they put forward other possible solutions when they could not resolve subsequent difficulties at a later stage. In order to improve the discussion about these subsequent problems, it was decided that, in the second version of the scenario, the alternative hypotheses should be dealt with more extensively, and at an early stage, by pupils themselves.

Activity 6 An inventory of alternatives to account for Gay-Lussac's law.
Activity 7 Investigation of the alternatives.
Activity 8 Selection of the most appropriate assumption(: adding to the framework).

In activity 6, possible answers to the problem are gathered in a plenary inventory. If not all the above hypotheses are put forward, the teacher can add those that are missing. It is expected that when pupils do comprehend that there seems to be more than one possible

solution, this observation in itself will drive them to find out, by means of comparison, which one is the best. In order to conduct this investigation, they not only need to see whether an increase in one variable will have the intended effect, but they also have to consider possible consequences, wanted or unwanted, of such an increase. Although it is expected that pupils have the ability to do this, they probably need strong guidance in order to do it in a sufficiently structured manner, which is necessary in order to make a valid selection. Therefore the investigation of activity 7 is structured by several worksheets (cf. appendix A), with identical format. The first part considers the effect of an increase of the specific variable on the force exerted by means of collisions. If such an effect is not expected, pupils switch to a new variable. If they do believe there will be an effect, they continue with the second part of the worksheet which deals with consequences. Because of the identical format of the worksheets, pupils will furthermore be able to judge possible additional hypotheses in more or less the same way.
It is expected that pupils will find the format of the worksheet useful in light of their motive, and that they will be able to evaluate all the alternatives. Their possible answers concerning the effect are summarised below:

- An increase in temperature of the balls does not make them collide more often nor with more impact, thus no effect on the force.
- An increase in speed of the balls implies that they will collide more often and with more impact, thus resulting in an increase in the force that they exert by means of their collisions.
- An increase in mass of the balls implies that they will collide with more impact, thus resulting in a bigger force.
- An increase in diameter of the balls without an increase of mass may be difficult to imagine and therefore may influence some of the answers in such a way that they will give the same answers as already mentioned in relation to that variable. Some pupils may recognise the difference between the two and will perhaps conclude that an increase in diameter will have only a small effect on the force.

The expected answers concerning the consequences are as follows:

- speed: no objections/unwanted consequences, apart from the question how it can happen.
- mass: a higher temperature would result in a bigger weight of the gas; and a similar question.
- diameter: a large increase in temperature would lead to visible sizes of the balls; and a similar question.

Not all groups of pupils will complete all worksheets, but each hypothesis should at least be judged by one group. In activity 8, all the results of the groups are gathered. The primary aim of the activity is for pupils to jointly make a decision and to ensure that all pupils understand why this particular hypothesis is chosen. In other words, all pupils should come to appreciate that from those alternatives that do have a sufficient effect on the force, which is exerted by collisions, they choose the one that has no unwanted consequences. It is the teacher's task to make this process of decision-making transparant, by managing the class discussion, and by putting the outcomes on the blackboard in such a way that pupils are encouraged to make the intended choices at the right instances.

The outcomes are summarised in terms of effect, objections and/or consequences at high temperatures. It is expected that pupils will intuitively assume that the weight of a fixed amount of gas corresponds to the sum of the weights of the particles. Although it seems obvious at first sight, the latter relation is quite complicated, for the particles move and therefore the weight should actually be understood as the force exerted on the lower plane of the container, due to the collisions of the particles, subtracted by the force exerted on the top plane. This more sophisticated understanding of this connection is not aimed for in the approach. Instead, we assume that pupils will intuitively establish this relation, exactly because it is so obvious at first sight, and use the connection in order to reject the hypothesis that the mass of the balls increases when a gas is heated. If necessary, pupils should be given the opportunity to check whether an amount of air indeed does not become heavier when it is heated, however they are likely to assume that the weight remains the same. In addition, the teacher can explain that these kind of measurements were in fact performed in the history of science (in connection with the phlogiston theory) and that the outcomes confirm their assumption. The increase in diameter remains a difficult issue. Pupils will have to trust the teacher when he adds to their own conclusions that when an amount of air is observed at extremely high temperatures, one still does not see any balls. If necessary, an explanation of why bigger balls hardly influence the force exerted by collisions, can be offered.

Whether pupils will indeed select an increase in speed of the balls as the most probable hypothesis, foremost depends on whether the teacher succeeds in making the process of decision-making sufficiently clear. The worksheets support his task to a great extent, but it remains to be seen whether the teacher will be able to extract the important information from pupils answers and to adequately summarise these on the board, whether pupils are sufficiently challenged to listen to each other and to further explain their own arguments, and whether they will accept the additional information from the teacher.

Arriving at a mechanism

Assuming that pupils come to select the increase of speed of the balls as the most probable hypothesis, the subsequent question is likely to arise during the class discussion, namely how can the speed of the balls increase when a gas is heated? How can that occur? This question was, in fact, put forward in history as well.

> Although a modern reader of Bernoulli is likely to jump to the conclusion that he identified the heat content or temperature of a gas with molecular kinetic energy, this conclusion was not stated explicitly. One of the handful of 18th-century scientists known to have mentioned Bernoulli's gas theory, Jean Trembly, was willing to accept the kinetic explanation of gas pressure, yet still complained that Bernoulli had not explained *how* heat increases the motion of particles. (Brush, 1976, p.20)

It seems natural to assume that progress can be made by focusing on processes of heating. In order to encourage pupils to account for the increase of the speed of the balls in terms of collisions, such a process of heating needs to somehow draw the attention towards these collisions. Therefore it was chosen to begin with a relatively simple example of heat conduction, in which there is direct contact between an amount of gas at a high temperature and an amount of air at a low temperature. Pupils already know that, apart from mixing of the two gases (i.e. convection), the temperature of the first amount will rise while the temperature of the latter will fall. Instead of the general question of how heating can cause the increased speed of the balls, the problem becomes much more specified, namely: how can the balls of the former amount come to move faster and those of the latter come to move slower?

In a similar activity during the first trial, some pupils suggested that fast moving balls will collide with slow moving balls to result in the latter moving faster. Although the first version

of the scenario varied from the approach sketched in this section, these results suggest that pupils can indeed be expected to imagine such a mechanism, even if they have not dealt with colliding objects in physics lessons before.
Because of the differences between the first and second version of the scenario, the first trial did not give any clear indications of other solutions to the problem. Therefore, at the beginning of the second trial, we did not know whether pupils would suggest other ways to explain how heating could cause the increased speed of the particles. We only expected that, in case such solutions were suggested, other pupils would find them less easy to understand and thus less convincing. Whether pupils indeed acted in this way, is an important aspect of the analysis in chapter 5.
A solution in terms of "moving faster after collisions with other faster moving balls" is expected to raise some new questions. Some of these will have to be postponed to another, future sequence, such as those referring to the cause of the (previous) acceleration of the initially faster moving balls. Other questions that are likely to be raised by pupils refer to situations in which a direct contact between the two amounts of gas is lacking. These will be dealt with in subsequent activities. While pupils apply the model during the latter activities, they will probably come to find the mechanism of transfer of momentum increasingly worthwhile. Moreover, while dealing with these more complicated situations of temperature rise, they will experience, although implicitly, that in all these cases the temperature of the balls does not have to be included in their explanations. This will prepare them for the assumption that the balls themselves stay invariant.

Activities and expectations

The process of arriving at a mechanism for heat transfer is guided by the following activities:
Activity 9 Arriving at a mechanism for the explanation of conduction of heat.
Activity 10 Application of this mechanism in more difficult situations.
Activity 11 Reflection on the results(: adding to the framework).

In activity 9, the first situation of conduction of heat is examined by means of a worksheet (cf. appendix A).

> The situation is introduced by the teacher, who explains that the pupils know that heating a gas causes a rise in temperature and that such a rise in temperature can be compared to an acceleration of the balls, but that the remaining question is: what makes these balls move faster? Or, in other words: with what should they compare the heating itself? Subsequently, pupils consider, either in groups or individually, the specific situation of heat flow, in order to answer the question. Afterwards, possible solutions are discussed plenary.

Based upon the results of the first trial it can be expected that at least some pupils will suggest that conduction of heat may be explained by means of collisions between balls with unequal speed. After some discussion, this solution is likely to be quite convincing. The subsequent question, concerning situations in which there is no direct contact between the two amounts of gas, will probably be raised by pupils themselves. If not, we still may expect that pupils will find it worthwhile to solve this problem, for otherwise the mechanism will not remain worthwhile.
The three worksheets of activity 10 all deal with a rise in temperature of an amount of air in a closed container (cf. appendix A). Twice, this air is heated by the surroundings, i.e. the air or water outside the container, and once the temperature is raised by means of work on the system, namely by pushing the piston of a bicycle pump[3]. The latter situation is offered in order to further encourage pupils to prefer the explanation in terms of collisions

in favour of any other solutions. When pupils notice that not only heating the gas, but also work on the gas can cause the balls to move faster, and that this phenomenon can be explained by means of a very similar mechanism, their remaining doubts may well disappear.
The worksheets are distributed among the groups in such a way that each phenomenon is examined at least once. Similar situations were discussed by pupils in the first trial. Heat transfer from the surroundings was then explained in the following manner:

- pupils imagined that the walls of the container would vibrate because of the collisions from outside and inside, i.e. when the balls on the outside move faster, they will collide against the walls more violently resulting in a "stronger" vibration of the walls which in turn makes the balls that collide against the wall from the inside move faster;
- or they imagined that the walls themselves consisted of balls as well, which move faster after collisions with the balls on the outside and, in turn, make the balls that collide against them from the inside move faster.

The situation including the bicycle pump may be more difficult. Pupils in the first trial reasoned too quickly, namely "the space in which the balls are moving becomes smaller, thus the balls collide against the walls sooner, thus they move faster". An additional worksheet (cf. appendix A) was therefore constructed, containing additional information. The latter should encourage pupils to find a better solution, namely that when the piston is moved the balls are pushed by the moving wall and are thus accelerated. In activity 11, the results of the groups are discussed plenary. Especially the situation of the bicycle pump needs extensive reflection, since it is considered to be more difficult and to decrease any remaining doubts. At the end of this activity, pupils' attention is focused on the framework of particle explanations. This will be elaborated in section 4.5.2.

Discussion of the approach

During development of the approach, it was assumed that activities 7 and 8 would explicitly show pupils that the most obvious connection, namely between the temperature of the gas and the temperature of the balls, is not adequate. We also expected, however, that pupils would not necessarily understand the connection between the temperature of the gas and the speed of the balls as of the same nature as the connections that were previously expressed. In the first trial, there were indeed some pupils who could not accept a similar correspondence. Although the latter conclusion was acknowledged during the construction of the approach, we did not sufficiently think through how this would influence the subsequent process. Since further thoughts concerning this issue emerged following the analysis of the results of the second trial, we will further discuss this in the next chapters.
Finally, in order to come to a more sophisticated account of the mechanism that explains the increased speed of the balls, pupils do need to know about the equations that apply to perfect collisions. In particular, they should comprehend the role of the masses involved. Pupils would then be able to understand that the particles of a macroscopic object that has a lower temperature than a second macroscopic object, can still move faster than those of the latter, provided that their masses are smaller. It was, however, decided not to explicitly deal with these matters, in order to prevent distraction of pupils from the main line of reasoning. Similarly, it was chosen not to elaborate on the fact that one should actually speak of the mean velocity of a collection of balls. The result of these choices may be that, when dealing with for instance even more complicated situations of heating, involving liquids and solids, pupils may become confused. Whether such effects occurred in the second trial, will also be discussed in the next chapters.

4.4.3 Additional hypotheses about the behaviour of the particles

Besides the process of choosing between hypotheses that link the state of the collection to the macroscopic system in different ways, pupils also need to further examine the behaviour of the particles themselves. The assumption that particles move in empty space, for example, cannot emerge directly from a further analysis of possible connections between variables of the model and macroscopic properties.

A good reason for an unusual assumption

When pupils come to find it plausible that the balls themselves do not change (cf. section 4.5.2), these particles are then considered so different from tiny bits that it may become easier for pupils to assume that there is empty space between them. But why would this assumption be made? In other words, which good reasons can be provided to induce the latter? One such reason can occur as a consequence of the correspondence between the temperature of a gas and the speed of the particles. For instance, consider a macroscopic object well isolated. In terms of the model, that means that the speed of the balls is not influenced by the outside world. Such a macroscopic object will keep the same temperature and thus, in terms of the model, the balls keep the same (mean) speed. In comparison with the movements of macroscopic objects in a medium such as water or air, it must appear strange to pupils that the balls in the above situation do not lose any speed, or that these, in fact, do not move slower unless it is as a consequence of collisions with slower moving balls (or walls that move in the same direction).
Such an observation will most likely raise the question of how these balls can indeed continue to move without losing any speed. Inducing such a problem should, however, not be attempted at an early stage, for then it may lead to abandonment of the model. However at a later stage, after the model is considered worthwhile and pupils furthermore have serious indications that gases really consist of permanently moving particles, such a theoretical problem may provide pupils with good reasons to accept or even propose hypotheses of empty space between these particles. For these same reasons it becomes necessary to assume that the collisions between the particles are perfect: mutual collisions between particles with the same speed, as well as collisions against fixed walls (of an isolated system), should also not influence the magnitude of their mean speed.

Activities and expectations

The above issues are dealt with after extensive reflection on the existence of the particles (cf. section 4.5.3). An increased confidence in this existence may also make it worthwhile for pupils to extent their knowledge on particles, for instance concerning the magnitude of their speed, or their size. Therefore, the following activities also offer several opportunities to further pursue such theoretical issues in order to come to an ever deeper understanding of the behaviour of matter.

Activity 15 Remaining questions concerning the particles themselves.
Activity 16 Investigations in order to answer the questions.
Activity 17 Reflection: additional hypotheses.

At some point in activity 14, which will be discussed in section 4.5.3, a mechanical simulation of the balls in motion is shown. This simulation clearly shows that macroscopic balls do not continue to move, but instead slow down, unless work is done to keep them going.

By focussing on the similarities and differences between the model and the simulation, the question of how the balls of the model can indeed continue to move without losing any speed, is likely to be raised.
In activity 15, pupils are asked to put forward further questions about the behaviour of the balls. These are gathered by the teacher in a plenary inventory. Besides the above problem, the question whether solids and liquids consist of the same kind of particles is likely to occur. In addition, the previous activities are expected to have raised several questions concerning the behaviour of the balls. The latter kind of questions are not deliberately induced, and therefore not all pupils may find these equally worthwhile. Therefore, the teacher explains that the question concerning liquids and solids will be further pursued by the whole class at a later stage, whereas several of the other questions are now dealt with by individual groups, according to their own choice.
In activity 16, each group of pupils starts to work on a specific problem by means of a worksheet (cf. appendix A). One worksheet deals with the question how the balls of the model can continue to move without losing any speed.

> In this thought-experiment, pupils are asked to choose between macroscopic objects to build a simulation of the model, because the problem concerning ongoing movement occurred when the latter was compared to movement in everyday life. In order to create the best simulation of this continuing motion, pupils will choose those objects that bounce maximally and select that medium that offers minimal resistance. The exact choice is not so important, as long as the arguments are in line with perfect collisions and no resistance. This argumentation will be used during the next activity.

The remaining three worksheets all concern the behaviour of the balls themselves. In two of these, pupils are offered help in estimating the speed of the balls. In the other, pupils are assisted in calculating the masses of balls of several kinds of gases[4]. Since these are not critical to the main line of concept development, we will not discuss these.
In activity 17, the results of all the groups are discussed plenary.

> During discussion of the simulation, the teacher introduces the scientific term "perfect collisions". In addition, he should emphasise that the conclusions do not only apply to the simulation that was designed in the worksheet, but also to the model. If there are pupils who do not accept the idea of empty space between the balls of the model, he should encourage them to explain their reasons, and eventually aim for some kind of compromise: if there is anything between the balls it cannot be another gas (for then it would consist of balls too) and it cannot slow down the balls in any way. The final assumptions concerning the collisions and the space between the balls are explicitly added to the list of hypotheses of the previous lesson.

Discussion of the approach

Although the question of how the balls of the model can continue to move without losing any speed is raised in a plenary activity, this problem is not necessarily tackled by all groups, since they are allowed to choose between several activities at this stage. The reason for this is mainly procedural, namely this design is in better agreement with the time schedule. Considering the fact that, in the literature, the acceptance of the hypothesis of empty space is supposed to be very difficult, one may argue that all pupils should deal with this problem themselves. However, since it is expected that the above context does provide pupils with a very good reason to assume empty space, it may also be expected that pupils will be able to explain this reason to those who did not examine the problem themselves. Whether this will indeed be sufficient for all pupils to accept the hypothesis, will be discussed in the next chapter.

Other questions are not deliberately induced, and therefore it may be doubted whether they will occur. Furthermore, if other questions are indeed raised, they may just as well concern other aspects of the behaviour of the particles, in addition to their speed and mass. Unfortunately, we were not able to design other activities that could assist pupils in finding answers to such questions. Therefore, the choice is only limited and, consequently, there is a considerable chance that pupils are forced to be engaged in solving problems that they do not find the most interesting. It would be best to have many different activities available, in order to ensure that most pupils can pursue their personal interests. However, several questions such as those concerning the size of the particles, cannot be answered satisfactorily until the model is modified in such a way that also the behaviour of liquids and solids can be accounted for. Nevertheless, further attempts should be made to provide pupils with more opportunities to solve problems of this kind at this stage.

4.4.4 Further development towards a model of gases, liquids and solids

The course of the process of teaching and learning is expected to gradually raise a new theoretical orientation (cf. section 4.2.3). Pupils are thus expected to see the point of adjusting the model in such a way that it can also be used to explain the behaviour of liquids and solids, and to have developed a sufficient view of how to proceed in this direction. During this subsequent process, pupils need to make choices again. More specifically, they need to consider which hypotheses of the model of gases they will retain, which they will replace, and which they will add. What kind of assistance should be offered to pupils in this process? An important problem at this stage was already framed in section 4.2.3, namely how long will they find it worthwhile to continue in this subsequent process? They may be satisfied quite soon, i.e. before they have sufficiently thought through whether their adjustments are indeed adequate. How can they be challenged to continue with the application and further refinement of the model? The first tested version of the scenario did not yet incorporate the behaviour of liquids and solids. Consequently, there are no results available that can contribute to an answer to these questions.

Choices concerning previous and new hypotheses

When pupils begin to consider whether they can change the model in such a way that they can also come to a better understanding of known behaviour of liquids and solids, it is important that they realise that previous particle explanations should be retained as much as possible. This means that the previously established connections between macroscopic and model variables are more or less maintained, while similar hypotheses are added. More considerable changes may be made to the hypotheses that determine the behaviour of the particles, as long as the hypothesis that the particles themselves do not change is maintained. In order to focus pupils' attention, the following two issues are emphasised:

- Similarities between gases on the one hand, and liquids and solids on the other. These should indicate that hypotheses concerning for instance the temperature, and even more importantly, concerning the immutability of the particles themselves, should be retained.
- Differences between the three states of matter. These should indicate that some hypotheses need to be added, or even changed.

If the previously developed framework of particle explanations is taken by pupils to serve as a guideline for further development, they will at least assume that particles of liquids and solids are also permanently moving, and that differences between the three states of matter correspond to differences in configuration. Maybe they will even immediately frame new hypotheses about interactions that determine these differences. These new assumptions are likely to concern some kind of mutual attraction. Consequently, they will implicitly establish a new correspondence between a macroscopic and model variable, namely the solidity of a sample of matter and the attraction between the particles.

Further refinement

Since pupils' subsequent work is expected to be guided by the framework, it has become possible for them to take even more responsibility in the further development of the model. The groups are therefore free to choose their own course of actions. Still, the scenario does contain several examples of possible actions in case a group is no longer able to frame challenging problems themselves. These examples belong to the following categories:
- answering further questions concerning previously established generalisations of the behaviour of liquids and solids;
- finding explanations for phenomena that are still quite difficult to explain, even by means of the new model;
- predictions of yet unknown behaviour of liquids.

In all these cases, pupils are asked to apply their model. During their discussions about these applications they may arrive at further refinements, such as a more precise description of the movements or configurations of the particles due to new assumptions about their interactions. If all groups work within the established framework, their adjusted models will be very similar. Differences will probably only concern further refinements.

These differences are made explicit during a conference at the end of the sequence. Being aware that they will have to explain their model during a conference will probably challenge pupils to thoroughly think through all the adjustments that they make. During this discussion pupils' attention is focused on even further refinement. Instead of being engaged in a contest, pupils are challenged to arrive at a final model that is even better than the one which they developed in their own group.

The final model(s) will probably be quite similar to that reported by Clausius in 1857:

> .. Clausius also suggested a qualitative explanation for the mechanism and thermal aspects of changes of state, based on the idea that molecules in solids and liquids are held together by their mutual forces. In solids each molecule vibrates or rotates around a fixed equilibrium position, while in liquids there are no longer any equilibrium positions but the translational motions do not carry the molecules far enough apart to allow them to escape the influence of their forces. (Brush, 1976, p.173)

At the end of the conference, the results are explicitly compared to this model. As with the model of Bernoulli, such a comparison may make pupils' own constructions seem even more important to them. In addition, the teacher also points at problems that indicate future developments of the model. Firstly, this will clearly show pupils that their model will indeed be further developed in future, and in that sense should not be considered as final. Secondly, it will give pupils some idea of what such a development will involve, i.e. how they may proceed in future lessons.

Activities and expectations

After the previous activities, pupils probably tend to assume that solids and liquids also consist of moving particles. This can be further encouraged by reflection on the fact that heating or cooling can give rise to changes of state. The sequence of activities that challenge pupils to adjust and apply the model to the behaviour of liquids and solids, starts with such reflection.

Activity 18 An outlook on a wider application of the model: liquids and solids.
Activity 19 Further development of the model.
Activity 20 Application and adjustments.
Activity 21 An inventory of adjusted models.
Activity 22 Comparison of the models.
Activity 23 An outlook on future developments.

At the beginning of activity 18, pupils and teacher reflect on their knowledge about changes of state.

The teacher reminds them that they know that the substance itself does not change during a change of state and explains that this can be an indication that also liquids and solids consist of the same kind of invariant particles. He asks pupils to think about similarities between gases, liquids and solids, and explains that such similarities make it plausible that the model will stay more or less the same. In addition, he reminds them that they already agreed only to make new assumptions when these were really necessary. Then he asks pupils to name some differences between the behaviour of gases, liquids and solids, and remarks that, in order to account for these, the model probably cannot stay completely unchanged. He explains that the aim of the next activities is to account for the behaviour of liquids and solids, and meanwhile to think about necessary changes or additional assumptions of the model. In addition, he reminds them that their approach will be the same as during previous lessons, thus asking questions and answering these by means of the model.

In order to get started, activity 19 provides pupils with a worksheet (cf. appendix A), which begins with an examination of differences and similarities between gases, liquids and solids. It is expected that, when reflecting on such differences, pupils will arrive at ideas for possible adjustments to the model. Although they themselves do not pose the question why these differences exist, the previous activities have made it worthwhile to find an answer, and have provided pupils with enough directions for solving the problem adequately. Being engaged in these modifications should bring pupils to pose and answer further questions about the behaviour of solids and liquids, such as those that were framed in section 4.2.3. Examples of such questions are added to the worksheet.

Activity 20 consists of several options for further actions, which pupils can choose if desired. Some of these concern phenomena that are still quite difficult to explain, even by means of the new model: the expansion of a metal, the smell of a solid, the growth of crystals, and the fixed temperature during a change of state (questions on paper, cf. appendix A). When pupils adjust the model within the previously developed framework, they will give answers similar to the following:

- the hole in the middle of a metal disc does not become smaller when the metal expands because then the balls would come closer together instead of further apart;
- some solids smell because the outer balls of the solid are bounced off by balls of air that collide against them; other solids do not smell because their balls are held together more strongly;
- during the process of crystallisation the mutual attraction is forcing the balls that slow down, to move in a specific pattern;
- in the case of boiling, some balls of the liquid, that come to move faster because of collisions with faster moving balls of the heat source, escape from the other balls of the liquid, and therefore those balls that remain are not accelerated (yet); in the case of melting, some balls of the solid are able to escape from their fixed positions because of collisions with faster moving balls of the heat source.

The other suggestions for further actions concern predictions.

One phenomenon was chosen which is quite surprising and not so easy to predict, with or without a particle model, and which can become comprehendible by means of the model: the boiling of water at room temperature, which occurs when the pressure of the surrounding air is lowered. If pupils do not recognise the influence of balls of air on the configuration and movement of balls of water, they will probably predict that nothing happens. If they do recognise such an interaction, they may predict that the evaporation proceeds faster, or perhaps that the water will start boiling. If they do not predict the boiling, they will need to make quite an effort to explain the phenomenon.

In addition, pupils are given the opportunity to observe Brownian motion in a liquid by means of a video[5]. In particular, they can qualitatively predict different motions at different temperatures, and learn about the quantitative predictions of Einstein and the verification by Perrin. Their own prediction will not be very difficult to arrive at, since it involves a straightforward combination of their explanation of heat transfer and their explanation of Brownian motion in air: the visible objects in the liquid will move more vividly at a higher temperature because the balls of liquid move faster and therefore collide more often against them and with more impact.

The conference starts with activity 21, in which each group is asked to explain their final model to the other groups by means of a poster and by means of a letter, written to Robert Brown as a homework assignment[6] (cf. appendix A). The aim of the activity is that all pupils understand the models of the other groups.

Subsequently, pupils are asked to compare their own model to those of others. Initially, this comparison is performed within their own group. In this way, pupils will feel more comfortable in expressing their ideas, while simultaneously they can practice their argumentation and receive feedback. The second part of activity 22 involves a plenary discussion.

Before groups of pupils start the initial comparison, the teacher emphasises that they should not just aim to defend their own model in the best possible way, but also discuss which of the models seems to be the most probable one, or use the models that are presented in order to build an even better one. If necessary, the teacher may repeat some guidelines that can be used to judge the models: whether it is effective, whether there are any hidden consequences, and whether the original model was changed as little as possible. Another important argument will probably be used by pupils naturally, because it follows from the previous lessons, namely to be able to explain as many phenomena as possible.

During the plenary discussion, pupils are invited to comment on other models. After some time, the teacher may be able to estimate in which direction the conversation might proceed and thus either:
- aim for an agreement;
- encourage pupils to build a new model by combining some of those presented;
- ask pupils to think about a possibly decisive experiment (he should not put one forward himself!).

The conference is closed when progression is no longer observed, when some pupils become bored, or when the activity is taking too much time.

In activity 23, pupils' models are compared to the one of Clausius, and an outlook on future modelling is provided.

The teacher explains that during the previous century, many scientists were not convinced that matter consisted of some kind of balls and could not agree how they should imagine the behaviour of these particles. He continues that one such model, which was offered by Clausius, proved to be very useful not only in order to explain but also for further development. The teacher shows some aspects of this model and compares these to the models that were presented by the pupils.

Then he explains that the model of Clausius was more elaborated, for he could also use it to explain how some substances reacted to change into new substances. He asks pupils how this could be, for the "balls" should not change themselves. After a brief discussion, he explains that Clausius thought that the "balls" themselves consisted of groups of other particles, that could separate and form new groups. Thus, the groups changed but the new particles themselves did not. The groups of particles could be compared to the "balls" and were called "molecules", the new particles were called "atoms". If the class discussion

about pupils' own models did not take much time, e.g. because an agreement was reached very quickly, the teacher may add some more historical information about other main scientists who contributed to the development of particle models, such as Boltzmann or Van der Waals.
Finally, the teacher points out that in future lessons the development of the model will continue, that maybe even atoms need to change in order to explain more phenomena, and therefore may need to be thought of as consisting of even more basic particles that are then treated as invariant. He summarises that the aim is to start with invariant particles, to give explanations in terms of the movement of and interactions between these particles, and to be able to explain and predict more and more phenomena. This summary is included in the hand-out which pupils receive at the end of the activity. This also contains a summary of the model which was developed during activity 1-17 of the sequence. The results of the remaining part of the sequence can be added by the pupils themselves.

Discussion of the approach

It is expected that pupils' models will continue to agree with the previously developed framework for particle explanations, and that initial adjustments are easily made. As a consequence, however, we may expect that pupils are satisfied at an early stage. The additional activities are therefore somewhat forced upon them. Although pupils are likely to recognise these as being in line with previous activities and they are allowed to choose those that they find most interesting, it still remains to be seen whether they consider them as sufficiently challenging in order to continue. The conference is, on the one hand, expected to serve as an additional procedural motive for pupils to thoroughly think through the adjusted model but, on the other hand, this may become less challenging once pupils realise that their models hardly differ.

4.5 The nature of particle models

4.5.1 Introduction

It was argued in chapter 3 that, in order to learn about the nature of particle models, pupils' attention should be focussed on the framework for particle explanations and on the existence of these particles by means of reflection on their own actions. In a problem posing approach, pupils themselves should come to find it worthwhile being engaged in such a reflection, and in such a way that they learn:
- what giving particle explanations consists in;
- which experiences influence their degree of belief in the existence of the particles.

The subsequent sections will each deal with one of these issues.

4.5.2 Reflection on particle explanations

Reflection on specific explanations

At some point during the sequence, pupils are encouraged to reflect on what giving particle explanations consists in. Before the latter activity takes place and in order to prepare pupils for this, specific explanations are already reflected upon at an earlier stage. During this earlier reflection, the foundations of the general framework are laid. Implicitly established connections between the model and macroscopic variables, as well as mechanisms according to which the particles behave, are made explicit. In addition, it is shown how these two kinds of hypotheses are used in specific explanations.

Activities and expectations

The first connections and mechanisms mentioned above are made explicit by the teacher in activity 5. When pupils explain their solutions to the problems that they raised in activity 4, these relations are incorporated in a format which is presented as a summary. An example of such a summary is given in figure 4.1.

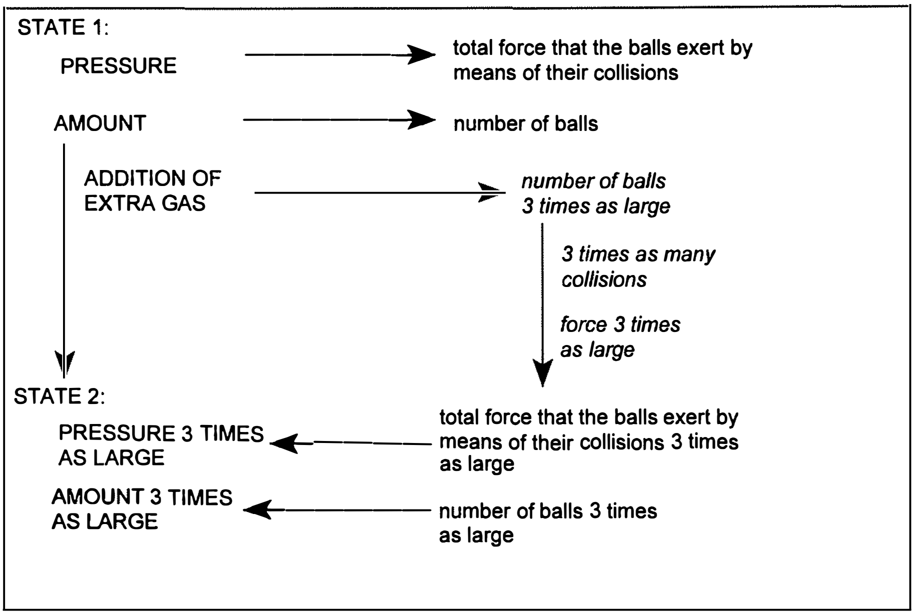


Figure 4.1 Summary of a particle explanation.

At the end of activity 8, newly established connections between macroscopic and model variables are explicitly reflected upon, when hypotheses are compared. For instance, when it is decided that the mass of the particles will not increase during heating of a gas because the weight of the gas does not increase during such a process, the teacher concludes that they implicitly established a connection between the mass of the gas and the mass of the particles. This conclusion is written down in a format that is similar to the previous summary. After the final choice is made, the connection between the temperature of a gas and the speed of the balls is also added to the previous ones. In addition, the worksheets of activity 9 and 10 (cf. appendix A) encourage pupils to write down their explanations in a similar format as the one that is shown in figure 4.1.

The invariance of the particles

When pupils have arrived at the mechanism of collisions between slow and fast moving particles, after which the first move faster and the latter slower, they no longer need to assume that the balls themselves become warmer. Having available such a mechanism, pupils are finally able to come to a deeper understanding of several generalisations that were part of their previously established macroscopic knowledge. Looking back at their explanations, they may come to realise that all the macroscopic changes were explained solely in terms of changes in position and speed of the particles. In other words: the particles themselves did not change. At that stage, the assumption of invariant particles probably does not appear as far-fetched as it would be at the introduction of the model and can further become a worthwhile principle.

Making pupils aware of these issues is an important aspect of the approach. It focuses pupils' attention on the specific way in which particle explanations are given. And that, in itself, can prepare pupils for further modelling activities, in the sense that it directs their attention towards the question whether all macroscopic change can be explained in a similar way. The purpose of working with the model thus changes from "coming to a better understanding of the behaviour of gases" towards "attempting to explain all macroscopic change by means of mechanisms involving invariant particles".

Activity and expectations

At the end of activity 11, the teacher asks pupils to reflect on the way in which they have been using the model so far. He explains that in all cases an amount of gas, with a specific pressure, volume, temperature and mass, was examined, and it was attempted to explain changes in the system by means of the model. He subsequently asks them how this was done. Looking back on their own explanations, pupils can probably explain that they:

- first compared the initial characteristics of the gas to a specific initial state of a collection of moving balls;
- then considered what would happen with these balls when a specific macroscopic variable was changed;
- and translated the final state of the collection back to the macroscopic level.

The teacher can then point out that when they follow this procedure, they make use of two kinds of relations: those between the macroscopic characteristics and the characteristics of the collection of balls, which function as a kind of translation; and those between the different variables of the model, which are necessary in order to find out how the collection changes. Furthermore, he asks the pupils whether, during such a macroscopic change, the balls themselves also change. They probably recognise that these balls only change in behaviour, but otherwise remain the same. This should be followed by a short reflection on the strong connection between change and invariancy: e.g. the characteristics of the (amount of) gas change, while remaining the same (amount of) gas.

Discussion of the approach

In the activities that are described above, reflection on the way in which particle explanations are given is initiated by means of presented summaries of pupils' own explanations. Although a summary can indeed be worthwhile to pupils from a procedural point of view, it lacks a content related motive. Since we have attempted to ensure that pupils do not need to make use of changing particles in their explanations, it becomes quite difficult to find such a motive for reflection. Therefore, we may doubt whether pupils will really be interested in looking back at their own explanations. At the time, we simply accepted this shortcoming and only attempted to make the reflection a little more interesting by means of a rather philosophical focus on the connection between change and invariance.

4.5.3 Reflection on the existence of the particles

Explanation and existence

It is not expected that pupils immediately wish to know whether a gas really consists of particles. Instead, the first activities of the approach are designed in such a way that pupils may become aware that it can be worthwhile to come to a better understanding of certain aspects of their existing knowledge, and that in some instances the use of a particle model provides them with a better understanding of those specific aspects. During such a process, pupils may gradually become more and more interested in finding out what matter really consists of, as an aim in itself.

Subsequently, also the question of the existence of particles can become worthwhile, for pupils may question whether they really have come to a better understanding if these particles do not exist. Meanwhile, this degree of belief in the existence of the particles will increase when pupils are able not only to come to a better understanding of more and more parts of previously developed knowledge, but also to make new predictions, and when they, for instance, arrive at the same specific results by quite different means. These issues should thus somehow be reflected upon during the process of modelling.

The course of this process would then not be much different from the way in which nineteenth-century scientists developed their ideas concerning the existence of atoms. Gardner (1979) argued that there was a gradual transition from an instrumentalist to a realistic acceptance of the atomic theory, and pointed at the gradual increases in its predictive power and the "testedness" of its hypotheses as being among the major causes. It appears that in the beginning of the nineteenth-century, the question whether particles existed, other than in the thoughts of scientists, was usually not an important issue. More important was whether theories about these entities could further explain the knowledge that was established so far. But, as more and more predictions concerning seemingly unrelated matters could be formulated and verified, many scientists became more and more convinced that matter really consists of such particles. Concerning molecules and atoms, the major breakthroughs were, on the one hand, the fact that estimations of Avogadro's number by quite different means all led to more or less the same result and, on the other, the experimental verification of Einstein's predictions concerning Brownian motion by Perrin (Nye, 1972). Although twentieth-century scientists progressively used models of quantum physics instead of classical particle models, the way in which their confidence in the existence of those new entities increased more or less stayed the same.

Activities and expectations

Explicit reflection on the existence of the particles is the main issue of the following three activities.

Activity 12	The value of the model developed so far.
Activity 13	Forming an opinion about the existence of the particles: the case of Brownian motion.
Activity 14	Evaluation.

Activity 12 aims to raise a new motive, namely wanting to find out whether gases truly consist of moving balls. Some pupils may already have asked, during previous activities, whether the balls really exist. In order to induce this motive for all pupils, they are encouraged to reflect on the value of the model developed so far. The aim of the activity is to establish pupils' opinions on this matter and to gather conditions under which the model would be worthwhile. Foremost, this activity should make pupils aware of their own point of view.

The teacher asks pupils what the value of the results is that they have reached so far. Some pupils may put forward that by means of the model they are better able to imagine how phenomena of pressure develop, or why heat flow occurs. Others may answer that they now know what happens to the balls but that they do not really value this knowledge. Maybe some even argue that they would only value this knowledge if the balls truly existed. If the latter argument does not occur, the teacher can either ask those pupils who doubt the value of the model whether they would find it more relevant if the balls did exist, or remind pupils that some of them already asked whether the balls existed or could be seen. Probably, many pupils will only find the model really worthwhile when the balls do exist. This is followed by a short discussion during which pupils can explain whether they do or do not believe that gases truly consist of moving balls. At this point the teacher gathers and repeats the reasons that pupils put forward in their argumentation and he asks those who doubt the existence of balls what it would take to become more convinced. Most pupils will probably think that they will change their mind when they can actually see these balls.

After the previous discussion, many pupils will want to know whether balls can be seen in order to become more convinced of their existence. The aim of the next activity is that pupils establish that, although balls cannot be seen through an ordinary microscope, the motion of much bigger smoke parts is indeed a new indication of their existence. During the activity pupils themselves formulate and check a prediction and are made aware that the outcomes influence their trust in the model. The activity is structured by means of a worksheet which focuses on the Brownian motion (cf. appendix A).

During previous activities, pupils have extensively thought about the effect of collisions of specific particles against other objects (i.e. particles or walls). The phenomenon of Brownian motion clearly resembles those previous situations, for it also involves collisions between the particles and other objects. Therefore, it can be expected that most groups will be able to make a prediction in this new situation, i.e. they will imagine that the parts of smoke will move in some way or another because of collisions with balls of air. If not all groups arrive at such a prediction, at least all pupils will be able to use the model in order to explain their observations afterwards. Some pupils will perhaps also think of an alternative explanation, such as vibration of the microscope, flow of air because of heating, or intrinsic motion of the smoke parts.

The extent to which pupils change their mind concerning the existence of these balls depends on the outcomes of their investigations, i.e. on whether their prediction was right and on whether they were able to think of a convincing alternative explanation. At the end of the activity some pupils may already formulate new questions about the balls, e.g. whether the balls could be seen by means of a microscope that can magnify much stronger, or how big they are.

In activity 14, groups of pupils are given the opportunity to compare their outcomes to those of others. In this activity it should become clear whether all pupils made the same observations, and the value of the experiment in the light of answering the original question should be discussed. The first aim of this class discussion is that pupils become aware that their degree of belief in the existence of the particles has grown, whether slightly or significantly, because it has become increasingly useful and, in particular, because it can not only be used to explain but also to predict. And that these, in themselves, are indications that the balls do exist. A second aim is that pupils come to understand that, although they may have more belief in the existence of these balls, they still know little about them. Pupils may then agree that it appears wise not to add any assumptions to the model unless they

really cannot do without. As an example, the teacher can ask them whether the balls need to be spherical, which pupils will probably not find a strictly necessary assumption.
In subsequent activities, only implicit attempts are made to further increase pupils' belief in the existence of the particles. For instance, eventually, more and more behaviour of matter can be better understood. Furthermore, in activity 16, the speed of balls of air is arrived at in two different ways, which is evaluated in activity 17. And in activity 20, some pupils will frame and test a new prediction. Finally, their arriving at a consensus model may also increase their confidence in the existence of the particles.

Discussion of the approach

In science education, Brownian motion is often put forward as proof that matter does consist of moving particles. In our approach, the phenomenon is used to make pupils aware that the confirmation of a prediction influences their degree of belief in the existence of particles. In other words, pupils are allowed to judge for themselves to what extent they find this phenomenon convincing. However, the framing of the prediction in itself is not completely motivated. Although the activity does become worthwhile in light of their motive to find out whether the particles exist, pupils have no reason to predict precisely the behaviour of visible smoke parts. The transition from the examination of air to the subsequent prediction is thus slightly forced.
At the end of activity 14, the emphasis on the hypothetical nature is expected to shift from "uncertainty about the existence of particles" towards "uncertainty about the nature of these particles". The latter perspective should encourage pupils not to make more assumptions than those that are strictly necessary. Although we expect that pupils will agree to this suggestion, it remains largely unclear what such an agreement involves. The suggestion itself is only a vague guideline for future modelling, for it is neither easy to determine how many assumptions underlie a specific explanation, nor is it clear what "strictly necessary" means. Its main function is therefore simply to prevent pupils from attributing all kinds of properties to particles without any restrictions. The major restriction in this respect was already put forward in activity 11, i.e. that during all macroscopic change the particles themselves do not change. The way in which pupils understand the new guideline thus very much depends on whether the principle of invariant particles is sufficiently understood and considered worthwhile.
By considering the existence of particles, pupils are encouraged to reflect on the way in which they have gathered information about (the existence of) these particles. In order to come to a better appreciation of the hypothetical nature of the model, pupils may also be encouraged to explicitly reflect on their process of modelling. Such a reflection is not sufficiently achieved in the approach. In this respect, the teacher is only asked to compare pupils' own way of arriving at results to the ways in which knowledge is gathered in science. For instance, at the end of the conference, in activity 23, the teacher is asked to summarise the course of the discussion. This overview can then be used in order to show pupils that personal models can be exchanged and that in science, as a result, consensus models emerge eventually. But this kind of information is only added by the teacher. Although it is based upon pupils' own results, it is not clearly motivated.

4.6 Summary

In the previous sections, a new approach to teaching and learning an introductory particle model was accounted for. In this account, the following preliminary answers were given to the questions that resulted from the general choices of chapter 3. The adequacy of these answers is evaluated in the next chapters.

Inducing a theoretical orientation

Before it is attempted to make the aim of coming to a better understanding of known behaviour of matter worthwhile to pupils, they need to have dealt with several aspects of this behaviour at a macroscopic level. Those areas of knowledge that have been selected concern specific gas laws, conduction of heat, changes of state and differences between these states. A strong motive for the introduction of a particle model has not been found. Instead, it has been attempted to show pupils in what sense it could be worthwhile to come to a better understanding of already established generalisations, and which sort of problems they need to solve in order to arrive at such an understanding. A reason to initially only consider gases is not provided, other than the expectation that what they will learn about gases will also be useful in coming to a better understanding of other known behaviour of matter. Initial problems that are raised are of the following kind:

- Why does air always want to spread out, or why does it always exert a pressure?
- Why are specific gas laws as they are?

At a later stage in the intended process of teaching and learning, a new (and stronger) theoretical orientation towards a more general applicability of the model is raised in two ways. Firstly, an extensive focus on the explanation of heat transfer is likely to encourage pupils to suspect a more general applicability. Secondly, the emphasis on the general framework of particle explanations is expected to adequately prepare pupils for further modelling, in the sense that they understand how they can fulfil the new motive. This further modelling is not initiated by means of specific problems, but only by means of a general focus on the three states of matter.

Introduction of the model

The model that is introduced consists of moving and colliding balls. Although we have not yet found a sufficiently strong motive for the introduction of this model, we think that it is sufficiently simple and that it can be applied immediately in order to answer the initial questions that are raised. The movement and collisions of the balls in itself are expected to at least not encourage pupils to consider these particles as tiny bits of a gas.
The model is illustrated by means of a computer simulation in order to make it even more intelligible. It is introduced by means of an analogy, which means that it is not assumed that a gas consists of moving and colliding balls, but only that its behaviour can be compared to the behaviour of such a collection of balls. It is expected that, because of this analogy, it stays uncertain whether a gas consists of particles and that pupils will be more willing to initially accept the model.

Modelling

It was chosen to encourage pupils to arrive at invariant particles by first comparing ways to connect the temperature of a gas to the model. In order to further explain Gay-Lussac's law, it is assumed that either the temperature, the speed, the mass, or the diameter of the balls increases when the temperature of the gas is raised. It is expected that pupils will eventually choose to connect the temperature of the gas to the speed of the balls, because an increase of the latter has the necessary effect on the force that is exerted by means of their collisions and has no unwanted consequences. We are not quite sure, however, whether pupils will immediately understand the connection as intended. Subsequent activities are designed in such a way that pupils are likely to arrive at a mechanism that can account for an increase of the speed of the balls, and will come to find this mechanism more and more fruitful in order to explain other situations of temperature rise. More specifically, we let them consider a relatively simple situation of heat flow, in which two amounts of gas of different temperature are in direct contact. We expect that they are able to explain this simple case by means of collisions between fast and slow moving balls, after which the slow ones move faster. This mechanism of transfer of momentum can subsequently be applied by them to more difficult situations of temperature rise. It is expected that pupils can imagine such mechanisms without having to have developed specific knowledge in previous science lessons.

Besides the process of choosing between hypotheses that link the state of the collection to the macroscopic system in different ways, pupils also need to further examine the behaviour of the particles themselves. In particular, the process of accounting for the possibility of ongoing motion of the particles provides pupils with good reasons to assume that the space between the particles is empty and that their collisions are perfectly elastic.

The previous activities are expected to gradually raise a subsequent theoretical orientation towards a more general applicability of the model. During the subsequent process, pupils need to consider which hypotheses of the model of gases are retained, which are replaced, and which they will add in order to also account for the behaviour of liquids and solids. Initially, pupils are assisted in this process by means of activities that encourage them to account for similarities and differences between gases, liquids and solids. Subsequently, they are challenged to continue with the application and further refinement of the model by means of examples of further questions about known behaviour of matter, of phenomena that are still quite difficult to explain by means of the model, and of situations that ask for a prediction.

The nature of particle models

By means of summaries of their own explanations, pupils are offered a framework of particle explanations and are encouraged to reflect on the invariance of the particles. Although we doubt whether this is a worthwhile activity for pupils, they may thus come to understand what giving particle explanations consists in and in which sense the particles differ from tiny bits.

In addition, evaluation of their explanations is expected to raise a motive to investigate the existence of the particles. After having successfully used the model to predict an unknown phenomenon, they are asked to discuss the influence of this event on their belief in the existence of the particles. At specific instances, pupils' own modelling process is explicitly compared by the teacher to the way in which scientists use and develop particle models.

Notes

1. An approach that is not yet sufficiently problem posing, but in which pupils do receive many opportunities to express their own thoughts and to be actively involved in the development of the above understandings about gases, can be found in Genseberger (1994 and 1998).

2. In fact, this model has already been used for educational purposes, for instance cf. Ogborn (1973).

3. The latter situation can also be found in an exercise in The Project Physics Course (1970), textbook chapter 11.

4. One of these methods of calculating the speed can be found in Ogborn (1973), chapter 3. The other method can be found in The Project Physics Course (1970), textbook chapter 11. Masses were calculated by means of presented information concerning the number of gas particles in a cubic metre and the densities of various gases.

5. This video has been made in Germany and described by Götz et al. (1987).

6. The design of this homework assignment was inspired by a paper by Nott (1994).

5. Description and analysis of the actual process of teaching and learning

5.1 Introduction and research design

The general ideas about teaching and learning a particle model, discussed in chapter 3, have been elaborated into a detailed educational design. The choices made to arrive at the design have been accounted for in chapter 4. In addition, we have argued why specific activities can be expected to build on previous ones and prepare for subsequent ones. The latter account is based on our expectations of pupils' motives and actions. In this chapter it is analysed to what extent the intended process of teaching and learning actually took place. Subsequently, chapter 6 deals with evaluation of the results and of the choices that have been made, in order to answer the research questions presented in the first chapter. In this fifth chapter, the course of the actual process of teaching and learning is also analysed by means of research questions, but these are much more detailed. Before we elaborate on the nature of these questions, the following sections contain information concerning the research design.

5.1.1 Practical information

The scenario was developed in close collaboration with an experienced physics teacher. He was asked to participate in this research because he had previously developed quite innovatory teaching materials (Genseberger, 1989). Furthermore, his style of teaching offered pupils many opportunities to express their thoughts, and he appeared open to testing a new approach. In addition, he worked at a special school, where pupils from high ability bands had not yet learnt about molecules and atoms in previous science lessons when they were 15 and 16 years old. However, during the first year of testing the scenario, new school policy forced the chemistry teacher to advance his lessons about molecules and atoms. Thus, it could only be ensured that pupils of this age had not yet learnt about the particulate nature of matter in physics lessons. The school also differed from traditional Dutch schools in more ways. For this research design the most important differing characteristics were:

- the classes of grade two and three still contained pupils of all ability levels; in other words, the "bridge year" was extended with two more years (cf. fig.5.1 and 5.2);
- lessons in chemistry and physics were not taught separately until grade four; below this grade they were integrated into science lessons which already started in the first grade;
- after third grade, pupils from the two highest ability bands, i.e. HAVO and VWO, were not separated, but stayed in the same class until the end of the sixth grade;
- all lessons initially took 80 minutes each, instead of 50; because of new policy this was reduced to 65 minutes during the second year of testing;
- science lessons always started with a class discussion, followed by a period of group work, the results of which were often discussed plenary at the end of the lesson; furthermore, pupils and teacher usually did not make use of a textbook; instead, pupils

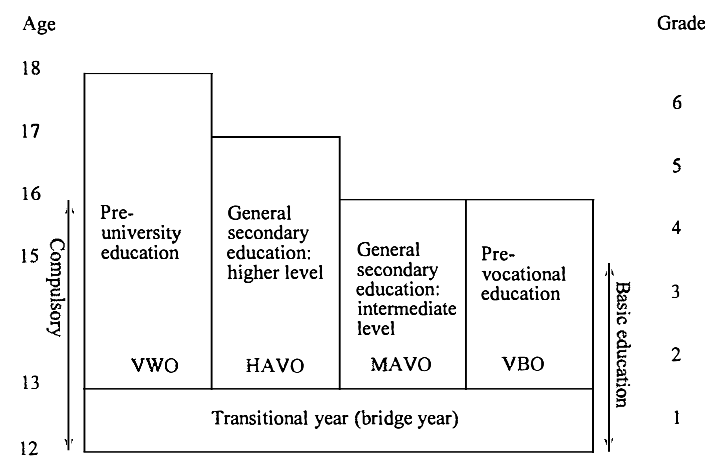


Figure 5.1 Simplified diagram of the Dutch school system: secondary education.

used worksheets and at home they wrote their own report of each lesson, which was read regularly by the teacher.

During development of the scenario, the teacher commented on draft versions and provided suggestions for improvements. The first complete version of the scenario was taught by this teacher, in one class, in 1995, just before the summer holidays. The class, fourth grade HAVO/VWO, consisted of ten boys and four girls. The first version of the scenario was taught in five lessons of 80 minutes. It did not yet contain any activities dealing with the application of the model to known behaviour of liquids and solids.
After the revision, the second more extended version of the scenario was taught by the same teacher, during the same period in 1996. Again, this concerned one class of fourth grade HAVO/VWO, which consisted of six boys and five girls. This second version was taught in nine lessons of 65 minutes.

5.1.2 Observation

Activities during the lessons

In both trials, the whole sequence of lessons was observed in the classroom. During class discussions, notes were made of what was put forward by pupils and the teacher. Meanwhile it was attempted to compare, as well as possible, the actual process to the scenario, and thereby to understand what was going on. This is often easier for a researcher than for the teacher, who also has to participate in the discussion and manage the activity. During group work, all groups were observed in order to see what pupils were doing and they

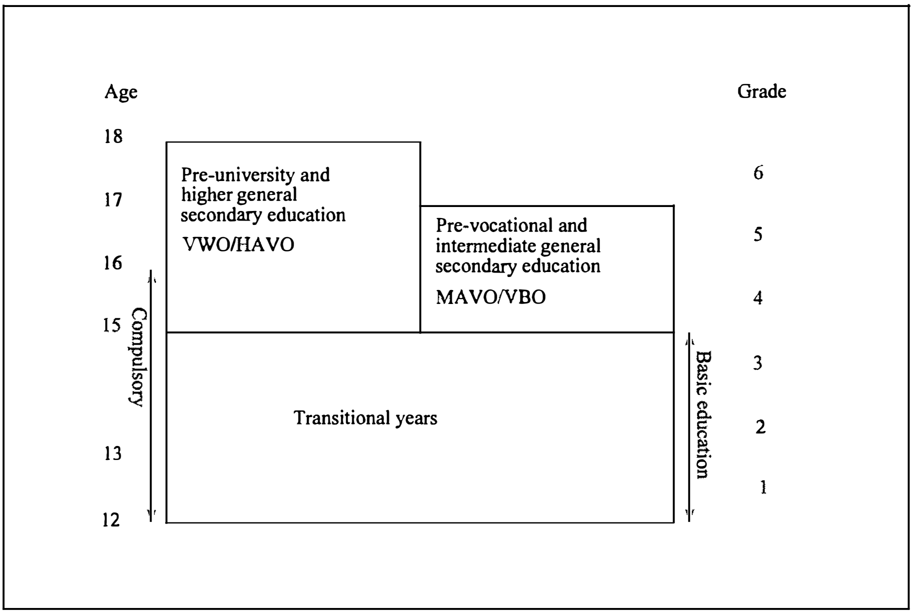


Figure 5.2 Diagram of the specific organisation of the school at which the scenario was tested.

were offered help where needed. This setting offered the opportunity to have conversations with individual pupils, and thereby to investigate for instance how activities were interpreted or what they meant by certain words or sentences that they said or had written down. Usually, also a brief consultation with the teacher took place, concerning the way in which the lesson had proceeded so far, what still needed to be done, how specific outcomes could be used in the remaining part of the lesson, etc.

In addition, the whole series of lessons was recorded. During the first trial, three tape recorders were used. One of these was carried by the teacher throughout each lesson. The second one (also) recorded all class discussions, as well as all other conversations of one group of pupils (three boys). The third recorder was carried by the researcher and only recorded her own conversations with pupils during group work. During the second trial, the latter also recorded class discussions. Furthermore, during this trial the second tape recorder was replaced by a video camera, in order to also record non-verbal aspects, and for future illustrative purposes. The camera started recording at the beginning of each lesson and during class discussions it remained at a fixed position in the back of the classroom without handling. When pupils began to work in groups, the camera was moved in order to record one group of pupils (three boys and one girl), until the next class discussion.

Activities in between lessons

After each lesson, the worksheets of all pupils were copied, as well as the reports made at home. Furthermore, the actual process in class was discussed with the teacher, by means of the notes that had been made. Usually this discussion took place on the same day and it was always recorded on audiotape. Depending on the available time between the lesson and the conversation with the teacher, the course of the lesson was reflected upon and those parts in which the actual process differed from the scenario were selected. During the evaluation with the teacher, ideas about these parts were exchanged and compared, and consequences for the next lesson were discussed. Also, other parts were dealt with, for instance, those that the teacher found difficult to handle or particularly enjoyed, and his own learning process was reflected upon. After the evaluation of each lesson, the teacher was assisted in preparing the next lesson. This preparation was not recorded.

Activities at the end of the sequence

In both trials, pupils were asked to express their opinion about the sequence as a whole, for instance in terms of how much they had learnt and which parts they had, or had not, enjoyed. This was structured by means of a series of questions (cf. appendix C) that they were asked to answer in their final written report. These questions were broad and open to encourage pupils to give their personal views about the series of lessons.

Also during the second trial, guided interviews were conducted with all pupils at the end of the sequence (cf. appendix D). To this end, pairs of pupils were selected who were approximately of the same ability level. This selection was based upon their performances during the series of lessons and was checked with the teacher. One pupil was interviewed on his own, because he had missed some crucial lessons. The interviews each took one hour and focused on different aspects of the sequence, namely:

- pupils' own final model;
- the framework which guided their particle explanations;
- the degree of belief in the existence of the particles;
- indications of the model and the framework in their own particle explanations;
- their opinion about the way in which they had been working during the sequence.

These interviews were not so much conducted in order to precisely establish how much pupils had learnt during the sequence, for this could only be assessed reliably in comparison with a pre-test. Instead, the results were mainly used to further clarify the data of the actual process of teaching and learning in order to evaluate the quality of this process as such. In some instances, at the end of the interview, pupils were also asked to explain some of their written work in specific worksheets, reports or discussions in class.

In addition to the discussions following each lesson, the teacher was also interviewed at the end of the sequence in order to give him the opportunity to reflect on the series as a whole.

5.1.3 Analysis

Procedure during the first trial

During and between lessons, a first impression of the quality of the scenario was obtained by comparing it, at first sight, to the actual process of teaching and learning. Afterwards, this impression was refined by means of a more detailed analysis. To this end, the audiotapes, together with all the available worksheets and reports of pupils were analysed, and all the outcomes were compared to the previously expressed expectations in the scenario. This analysis was reviewed by a second researcher. The final reports consist of summaries of the course of each lesson, an evaluation of the previously expressed motives, expectations and aims of each activity in terms of the extent to which they appeared to be appropriate, and a selection of fragments of conversations which illustrate the outcomes of the analysis. In addition, a summary was given of the evaluation of the sequence by pupils and teacher, the major shortcomings of the scenario were pointed out and some suggestions for possible improvements were made. The report was discussed with the teacher. The outcomes of this discussion were taken into account in the process of revising the approach and writing the second version of the scenario.

Procedure during the second trial

As in the first trial, a general impression of the quality of the scenario was obtained during the second trial, which was refined afterwards. Again, the tapes and all the available materials of pupils were analysed and compared to the scenario, and this analysis was reviewed by a second researcher. This time, more specific research questions were derived from the structure of the scenario. Subsequently, summaries were made of the course of each lesson, according to what seemed relevant and necessary in order to answer the research questions. Also, summaries of pupils' written reports were made and all the interviews were transcribed. Based upon the analysis of the tapes and pupils' materials and the comparison to the scenario, the questions were answered and fragments of conversations were selected in order to illustrate the answers.

5.1.4 Procedure of the report in this chapter

The analysis in this chapter will not show whether each individual expectation of the scenario was verified. Instead, it will be outlined how specific results of the first trial have been taken into account during revision of the scenario, to what extent during the second trial the course of the process was clear and worthwhile to pupils, and which new indications were found for the way in which we may further enhance pupils' conceptual development. Therefore, the following issues are emphasised in the specific research questions:

- To what extent were specific motives raised and were the subsequent activities adequate in order to fulfill these motives? That is, considering their previous experiences, did pupils find it worthwhile to continue in a specific direction? Did they develop ideas about the way in which they could make progress in that direction? Did the subsequent activities allow them to act accordingly?
- Does the actual course of the process generate new ideas about the teaching and learning of a particle model? That is, can we come to a better understanding of what pupils say and do? As a result of such better understanding, can we arrive at indications for a further improvement of the intended process? Can we already estimate, to a certain extent, whether such a process can indeed take place?

The description and analysis of the course of the actual process is presented in the same format as was used in chapter 4, which means that parts of the scenario that have been discussed in section 4.x are evaluated in section 5.x. Each section is structured by means of the specific research questions, which are briefly answered immediately. Subsequently, these answers are illustrated by means of fragments of conversations and of pupils' written reports, and by means of short descriptions of the course of activities. Resulting new ideas about teaching and learning a particle model are shortly reflected upon in the discussion of each section and summarised in the final section of this chapter. More extensive reflection takes place in the next chapter. Fragments of pupils' conversations either concern the first trial (code "1:x,y" referring to first trial, lesson x, fragment y), or the second trial (code "2:x,y"), or the interviews at the end of the second trial (code "int." followed by an indication referring to the pupils involved). Fragments of pupils' written reports either concern their homework (code "HW2:x" referring to homework after lesson x in the second trial), or their worksheets used in class (code "WS2:x.y" referring to worksheet number y used in lesson x in the second trial), or their final report (codes "FR1" and "FR2" referring to the final report at the end of the first and second trial, respectively).

5.2 A theoretical orientation towards previously developed knowledge about behaviour of matter

5.2.1 Introduction

In chapter 4, it has already been argued that a strong motive for the introduction of the model was still missing. Nevertheless, the approach did intend to prepare pupils for this introduction. In section 5.2.2 it is discussed to what extent pupils were indeed prepared for the introduction in the intended way. At a later stage, pupils were expected to gradually develop a theoretical orientation towards a more general application of the model. In section 5.2.3 it is discussed to what extent this new theoretical orientation was indeed raised.

5.2.2 The attempt to induce an initial theoretical orientation towards knowledge about behaviour of gases

The approach intended to prepare pupils for the introduction of the model in two ways. Firstly, it was attempted to show pupils, by means of reflection on their own previous results, why it can be worthwhile to come to a better understanding of previously established regularities in the behaviour of matter. Secondly, it was attempted to show which specific regularities could not yet be further explained. In this section it is discussed to what extent these attempts succeeded.

Coming to a better understanding can be worthwhile

At the end of the first activity, pupils were expected to understand that, in physics, they had arrived at knowledge of an ever more general nature, and that such knowledge had been worthwhile because it could be used to explain and predict even more phenomena.

Question:

To what extent did pupils understand that it could be worthwhile to come to a better understanding of already established generalisations?

Outcome:

Pupils most likely did have a vague idea of what would happen in subsequent lessons, namely they were going to investigate why specific established regularities "are as they are". They most likely did not sufficiently understand that the outcomes of their subsequent work would be knowledge of a more general kind by means of which more could be explained and predicted. Therefore, it seems that it did not become sufficiently clear why coming to a better understanding of known regularities could be worthwhile.

Illustration of the outcome:
Pupils did agree on which of the presented regularities were scientific and why. Furthermore, several pupils could explain why these regularities "are as they are", by referring to more general regularities. In addition, the teacher was able to refer to some familiar examples to argue that these more general regularities did enable them, in the past, to explain similar phenomena and to make new predictions. He also indicated that a further question could still be asked. This was expected to be sufficient in order to show pupils that it can be worthwhile, in general, to come to a better understanding of already established generalisations. So far, the intended course of actions was followed.
However, the teacher continued by giving pupils the opportunity to answer such a further question, which they indeed could to their own satisfaction. He then did not show in which way their answers, again, were examples of an improved understanding by means of which more phenomena could be understood and/or predicted, and he also did not indicate that a further question could, again, be asked. In other words, the surplus of this deeper understanding was not emphasised, nor that it could still be worthwhile to continue in this direction. As a consequence, it is likely that pupils could not comprehend both these issues. One pupil, who was asked to explain what he thought they were going to do in the next lessons, seemed to appreciate that the outcomes of their subsequent work could be used to explain even more phenomena, which she described as "in order to be able to answer even more questions". But in their reports pupils mainly pointed out that they would continue to ask "why-questions". None of them mentioned being able to explain more phenomena or to make new predictions.
Compared to the first trial, there was a larger emphasis on asking further questions. This was mainly due to a better instruction of the teacher, and can be considered an improvement. Still, the purpose of asking these further questions should also become clear. It is difficult to estimate whether the latter aim could have been reached if the intended course of actions was followed more strictly by the teacher.

Regularities that cannot yet be further explained

At the end of the second activity, pupils should have come to appreciate that there are specific questions concerning known behaviour of gases, that they cannot answer other than "that is just the way it happens" or "that is just a property of a gas".

Question:

Did pupils understand which kind of regularities they could not yet further explain?

Outcome:
During the first trial, the teacher was able to show pupils that they could not yet further explain why air wants to spread out. Therefore, the scenario was not altered at this point. However, during the second trial, pupils did not reach the same conclusion. Instead, they were able to answer each further question of the teacher in some way. They did not come across a problem and thus did not reach the point where they appreciated that a specific regularity cannot yet be further explained.

Illustration of the outcome:
In the first trial, it was found that pupils mainly focused on the experiment, which they could already explain, instead of on the generalisation by means of which they were able

to explain the phenomenon. Nevertheless, the teacher could point out that they could not explain why air always spreads out, other than calling this behaviour "a property of air".

(1:1.2) [T=teacher]

T: How could you explain that the bag expands, that it becomes spherical, what happens? Can you explain that? Is there something that we already..., how you can..., *Na*?

Na: Well, it is a property of air that it wants to, wants to spread out in the whole space. So the air in the bag wants to spread out in the whole thing.

(...)

T: ...what *Na* really was saying was that, well, that when the air outside is gone, then it spreads out in the whole space, but that is how you can see, when you remove the air outside, that is exactly how you can see that it spreads out in the whole space, but why does it do that?

Na: Can't that be a property?

T: That can be a property, yes. Exactly, it can be a property, which we can, for which you cannot, for which you cannot find an explanation. That could be possible. For ehm, a pencil falling down, then you can say that is, that is because of the gravitational force, but why does that happen? Well, and that is a question that ehm, that really nobody knows how to answer. But also [an answer] that physicists always keep searching for, why it happens like that.

During the second period of testing this result was not reached. Again, pupils kept focusing on the experiment, which they could already explain in macroscopic terms, but this time the teacher could not show them that there still was a question that they could not answer other than "that is a property of air". The reports of many pupils also clearly show that they did understand that they were supposed to ask further questions, but did not see that the final question could not be answered satisfactorily. For example:

Al(HW2:1):

When you remove the air around a plastic bag [filled] with air, the bag becomes bigger.(regularity) But now we ask "why? Because the air pressure around [the bag] becomes smaller thus the bag becomes bigger. But "why?"

As a result many pupils who participated in the class discussion were quite satisfied with their answers, in which they considered the difference between the pressure inside and outside the plastic bag. In other words, in this specific case they did not see any problem and thus did not reach the point where they could only answer something like "that's just the way it is".

Although, in the first trial, the teacher succeeded to show which regularity could not yet be further explained, pupils were not sufficiently challenged to pose similar problems concerning similar regularities. Nevertheless, they were forced to pose such problems while reflecting on known experiments concerning phenomena of air. During that activity, many pupils showed that they had not developed the necessary macroscopic knowledge, for they often did not agree about what would happen when a specific experiment was performed or about the way in which that phenomenon should be explained at a macroscopic level. In these situations, pupils were involved in lively discussions and seemed determined to solve their problems. Such an atmosphere was not observed when pupils were asking questions about macroscopic knowledge that they did agree about. Although they often did not agree which question should be asked, these discussions were far less lively, and pupils did not seem challenged to pose these questions, nor to search for answers. Only one pupil had included all the questions that her group had gathered in her report of the first lesson. Apparently, the other pupils did not consider them very important. Subsequent reflection on this list of questions did not raise any enthusiasm. On the contrary, the length of the list and the absence of any hints how to answer these questions, even seemed to depress some pupils. This result, again, indicates that pupils did not understand why posing these problems could be worthwhile.

5.2.3 A theoretical orientation towards a more general application of the model

The new theoretical orientation that the approach intended to raise at a later stage, consisted of two aspects, namely the suspecting that solids and liquids also consist of the same kind of particles, and a sufficient idea of how to proceed in this new direction, i.e. in such a way that the final model still fits in the previously established framework. In this section it is discussed to what extent both aspects were found in pupils' expressions.

Suspecting a more general applicability

During the process of modelling, pupils were expected to gradually begin to suspect that the model could also be applied to known behaviour of solids and liquids.

Question:

Did pupils indeed suspect a more general applicability?

Outcome:

This more general applicability was suspected by many pupils. In several explanations that were previously given, it was already assumed that water, and even containers, consisted of balls too. Furthermore, the question whether liquids and solids also consist of balls was put forward during the inventory of remaining questions (activity 15). An additional, but less strong indication of pupils' suspecting the general applicability, is that the class discussion about a possible wider application of the model proceeded according to our expectations.

Illustration of the outcome:

The answers of the first item of the worksheet of activity 4 (cf. section 5.3.3) show that pupils automatically assumed that water also consists of balls. At that stage, the cardboard and the glass were still considered at a macroscopic level. Following this activity, while reflecting on the results in his homework, one pupil already asked whether water should also be thought of as balls. In explanations of the more difficult phenomena of heat transfer (activity 10), the surrounding water was again considered to consist of balls. One group further suggested that the container itself could consist of balls.
The class discussion of activity 18 more or less proceeded in the way it was planned. The reflection on changes of state and on transport of heat encouraged pupils to assume that solids and liquids existed of the same kind of particles as gases, and similarities and differences between the states, which were briefly mentioned, indeed gave pupils some ideas about necessary adjustments.

Knowing how to continue modelling in such a way that the final model fits into the framework

Besides suspecting a wider applicability, previous activities were expected to have prepared pupils for knowing how to proceed in adjusting the model.

Question:

Did pupils know how to continue their modelling process and did their final models still agree with the framework of particle explanations?

Outcome:

Pupils clearly showed that they knew how to proceed, and even indicated that they did not need any help to arrive at adjustments of the model. Most of these adjustments seem to fit in the framework. However, a fraction of these indicate either a lack of macroscopic knowledge or a too weak correspondence between the temperature and the speed of the particles.

Illustration of the outcome:

Following the class discussion concerning differences and similarities between gases, liquids and solids (activity 18), pupils were ready to adjust the model. Although the teacher noticed this, he forced them to use the worksheet of the next activity anyway. This was not appreciated by the pupils.

(2:7.7) [T=teacher]

Ni:	Shall I explain?
T:	Alright, you're starting....
Ni:	Yes we're starting right away.
T:	Yes, you begin at the front side, right, that...
Ni:	Oh, is that necessary?
T:	...that worksheet will help, yes the worksheet will help you to pose these questions and to...
Ni:	Oh, that's a pity.
T:	...do that more or less in a structured way, no but it is, you can still think through your own things, there are no pre-arranged things, only the kind of questions that you need to consider.

(2:7.8)

Bo:	...that is also why, a liquid begins to boil, a gas is much more ehm spread out...
Fr:	Then it goes like bubble, bubble, bubble.
T:	Yes, that is exactly how you should consider these things, but I want to give you a hint, that is to first do that worksheet, for it'll help you with the way of ehm, reasoning that you will more or less ordered, in an orderly way ehm, at the front side there are, you can, in a certain way, you can build the model in a certain way, and at the back side you will solve problems, but these are just the questions that you already had, it only helps with ehm, the best steps to do next, right?
Fr:	Why? What are we supposed to do here?

It appears that the previous class discussion had already prepared pupils sufficiently in order to adjust the model. They clearly showed that they would like to proceed in their own manner. Since the teacher insisted, they did eventually start to read the worksheet, but they still barely used it to make the initial changes. Further refinements, on the other hand, were indeed partly made as a result of the questions in the worksheet. This will be discussed in section 5.4.4.

The framework of particle explanations, established during previous activities, was intended to guide pupils subsequent modelling: pupils were expected to continue to assume that the balls themselves do not change and, as a consequence, to search for new assumptions concerning the interactions between the particles in order to account for new changes of the collection as a whole. In order to analyse whether the framework did function as a guideline, pupils' final models are discussed below.

During the final lessons, only two groups remained because two pupils were absent. At the start of the conference, both remaining groups explained their models by means of a poster and a letter to Robert Brown.

(2:9.1)

Fr: Well we thought that with a gas elun the balls move far apart. And that, we thought that the balls have an attractive force on each other. And when they move fast then, then they sooner free themselves from the attractive force on each other. And with a liquid, the balls move a bit closer to each other, that means that they free themselves a bit less quickly from the attractive f, attractive force. And with a solid liq, solid ehm the balls are close together and then the attractive force has more force on which they, yes then they also stay close together and a low speed. Ehm. The shape, the mass and the volume, volume of a substance is different for each substance and when you're going to boil a liquid, ehm, when a, if a liquid has a high boiling point it means the attractive force of the balls is stronger and if the liquid has a low boiling point then the attractive force is less strong. And when you're going to melt a solid and it has a low melting point then there is a small attractive force between the balls and if it has a high mel......, melting point then the attractive force between the balls is bigger. Yes, that's what we thought.

The letter that was read by this group did not add any information. The model of the other group was slightly different.

(2:9.2)

Iv: Our model is nearly the same as yours, probably a bit different... ehm. The balls move in a gaseous state they move very fast, that is different for each ehm substance ehm the speed but, in a gas they move very fast, are far away from each other. Ehm with ehm liquid they are ehm close together but ehm, and they still move and in a solid, yes o yes, they circle around each other, when you have a ball and then they move around it ehm these, and ehm with a solid they all stand still. Alright, they turn, they vibrate (laughs). I do know!

Al: Is also on your poster.

Iv: Is that right? Alright, well that was about it. And ehm about the temperature, when it, ehm each time the temperature gets higher then ehm the, the frequency on ehm which they turn is also ehm higher.

The letter that was read by this group added some aspects.

Ni (HW2:8)

The differences between the balls are caused by the size.(...) This distance is caused by the speed and the attractive force of the balls. (...) The temp is now so high that the balls are going to move around each other. (...) The speed of the balls is now so big that they go off the curve. The balls now move so fast that they're no longer bothered by the mutual gravitational force.

These fragments show that, in both final models, the particles did not change and new assumptions were made concerning interactions, namely a mutual attractive force, as a result of which particles were assumed to be closer together when they move slower. In addition, the balls of different substances were assumed to differ in shape, mass, size and attractive force, and the second group also assumed that the balls of liquids circle around each other.

However, these final models do not seem to fit into the framework completely, for there seems to be a strong correspondence between the speed of the particles and the macroscopic state of the substance: the particles of the gas move fast, those of the liquid slower, and those of the solid even slower. *Iv* initially even stated that the balls of a solid "all stand still", but he subsequently did seem to assume that these balls vibrate. Standing still thus most likely refers to a zero nett movement. The strong correspondence between the speed of the particles and the macroscopic state of the substance may indicate a too weak correspondence between the speed and the macroscopic temperature, for the particles of, for instance, a gas and a liquid of the same substance at the same temperature, should have identical speeds. However, it may also indicate a very strong connection between the states of a substance and the temperature at the macroscopic level. In other words, pupils may not have sufficiently realised that two different states of the same substance can occur at the same temperature, and that consequently the particles of both amounts can have the same speed. In the latter case, the knowledge that pupils had developed previously was not sufficient. Nevertheless, even if pupils macroscopic knowledge is improved in this respect, more emphasis on the connection between the speed of the balls and the temperature seems adequate.

Finally, it seems that pupils assumed a too large mutual distance between the particles of liquids, in comparison to the distances between the particles of gases and solids. This was not discussed in class, but it foremost seems to be caused by a lack of macroscopic knowledge. Most likely, these pupils did not realise, or never explicitly learnt, that the volumes of a specific amount of substance in the solid and liquid state are more or less equal, and much smaller than the volume in the gaseous state. Explicit reflection on this fact would probably lead to the assumption that the distances between particles in solids and liquids are similar and much smaller than those between particles of gases.

5.2.4 Discussion

Based upon the analysis of section 5.2.2 it can be concluded that pupils were not sufficiently prepared for the introduction of the model as intended. Due to the actual course of the process, many pupils most likely did not see the intended connection between the first and the next activities. Although the teacher explicitly mentioned that they would initially only consider gases following the first activity, the scenario did not emphasise that this would serve as an example for other phenomena as well. In addition, it seems that pupils did not sufficiently appreciate why it could be worthwhile to come to a better understanding of known behaviour of matter. In the second trial, moreover, there also was no connection between the first and second activity. This is probably due to the way in which the second activity was carried out. Pupils' attention was too narrowly focused on the particular experiment in that activity, which they felt they could already explain satisfactorily. So for them there was no problem and the only clear similarity between the activities must have been the repetition of unspecified "why-questions".

It seems, however, that the second version of the scenario, if properly carried out, can still show pupils, on the one hand, why it can be worthwhile to come to a better understanding of specific behaviour of matter and, on the other hand, which kind of regularities they cannot yet further explain. To this end, there should be more emphasis on the reason for trying to come to a better understanding of known behaviour, namely because it may enable them to explain and predict more phenomena. In addition, whether pupils' attention is mainly focused on the particular experiment of the second activity or on the more general knowledge of the behaviour of air, or even of gases in general, in all cases pupils should become aware that specific properties of air, or gases, account for the observed behaviour and that they make use of these properties in their macroscopic explanations. The question "why these properties are as they are" was never posed before, and should now become the central issue. With these adjustments, an appropriate initial theoretical orientation is, however, still not raised, for pupils are not provided with an idea of how to answer the latter question.

How the approach should be further adjusted in order to induce an appropriate initial theoretical orientation, is discussed in section 6.4.3.
The theoretical orientation towards a more general application of the model emerged to a reasonable extent. The results indicate that, at the beginning of this phase, pupils can handle even more freedom in the process of modelling. When the initial class discussion of activity 18 is retained, then the worksheet of activity 19 seems unnecessary, for pupils seemed to have a sufficient idea of how to proceed. Further questions, such as were given on the back of this worksheet as part of activity 20, are still important, as will be shown in section 5.4.4. Furthermore, the knowledge that pupils have previously developed needs to be improved, and more emphasis on the correspondence between the speed of the particles and the temperature seems necessary.

5.3 The introduction of a particle model

5.3.1 Introduction

In the scenario, the model was introduced as a means to come to a better understanding of a specific regularity. It was expected that pupils can immediately use the model in order to answer the question that was meant to be raised in the previous activity. This immediate success should make pupils more willing to continue working with the model. In section 5.3.2 it is discussed to what extent pupils accepted the model when it was introduced. Following introduction, the model was intended to be used in order to explain other known phenomena of gases and it was expected that successful application in these instances would enhance pupils' acceptance of the model. In section 5.3.3 it is discussed how pupils used the model in their subsequent initial explanations.

5.3.2 Introduction of the model

In the second version of the scenario, the model was introduced in the third activity. In order to analyse to what extent pupils accepted the model, it is investigated whether they considered the model useful for the explanation of the specific phenomenon that was selected in the previous activity. In addition, it is discussed to what extent the special way of introducing the model, by means of the analogy, contributed to acceptance of the model.

The model as a useful means to answer the question

It was expected that pupils would immediately see how they could use the model in order to answer the question that was meant to be raised in the previous activity. However, the previous activity did not clearly result in such a question. Nevertheless, pupils were asked to apply the model to this specific phenomenon.

Question:
Did the model seem useful to pupils when it was introduced?

Outcome:
The model indeed seemed useful to pupils, for none of them made any objections when it was introduced, and an explanation of the previous experiment was given by them soon afterwards. Two remarks should however be added, both of which will be elaborated below.

Illustration of the outcome:
In the first trial, the introduction of the model was accompanied by a demonstration of an electrical device in which little balls were kept in motion by means of vibration. This resulted in serious doubts, mainly concerning the cause of the ongoing movement of the particles of the model. During the second trial, the model was illustrated by means of a computer simulation. This time, not one pupil expressed doubts. As they were not distracted by problems concerning the cause of movement, pupils' attention may have been more focused on the model and the way in which it could be used.
Since none of the pupils made an objection, it seems that they already suspected that this model might be quite useful. One pupil even immediately used the model to explain the experiment of the previous activity:

Iv: And then they bounce further and further apart, you know like bang bang, and then they touch the sides all the time.

Another pupil expressed himself as follows:

Ni: I think that when (..), in the bag, so many of those balls push against the wall all the time and also just as many of those balls bounce against the outside (..) then the bag remains just as big, but if more balls are being removed then there is less hitting against the outside of the bag and thus it will become bigger (..).

It seems that the model could immediately be used to these pupils' own satisfaction, which indicates that they considered the analogy worthwhile.
However, two remarks need to be made. Firstly, this third activity is a plenary activity. The fact that none of the pupils made any objections does not necessarily mean that none of them had any objections, and the fact that two pupils immediately applied the model does not necessarily mean that all pupils could apply the model to that specific situation. This seems unlikely however, as the pupils and teacher had already created a positive atmosphere during the past nine months, in which pupils had become used to ask for further clarification whenever considered necessary. Therefore, we may assume that pupils who did not understand the explanations that were given, would indeed have asked for such a further clarification.
Secondly, the answers demonstrate that pupils mainly focused on the experiment, instead of on behaviour of which they could only say "that is just a property of air". This result can be understood as a consequence of the course of the second activity, which did not clearly challenge pupils to focus on the latter. Thus, the answers that were given differ from the ones that were expected (cf.section 4.3.3), because they are explanations of the specific phenomenon, and not of a more general regularity in the behaviour of gases. This conclusion is supported by many of pupils' reports, in which similar explanations of the specific phenomenon were found. Since the previous activity already showed that pupils were quite satisfied with their macroscopic explanation of this phenomenon, the model did not help them to solve a problem, for they did not conceive any problem. Instead it functioned as an additional way to explain the outcomes of the experiment. Some pupils even explicitly mentioned in their reports that they used the model in this way:

Jen(HW2:1): You can also explain it in a different way.
Vs(HW2:1): You can also design a model, think about it and then put forward an hypothesis.

Although pupils could already explain the experiment macroscopically, the model nevertheless did seem to add to this explanation. In addition to the abstract comparison of the pressure inside and outside the bag, they were now able to imagine how the balls on the inside collided more often against the bag than the balls on the outside. In pupils' reports, almost all explanations of this experiment contained words that referred to collisions. This detailed mechanism of collisions appears to have provided them with a clear image of the course of the phenomenon. Implicitly, they may therefore also have arrived at a better understanding of why air exerts a pressure. In section 5.3.3, we will analyse whether these detailed mechanisms of collisions continued to be part of pupils' explanations.

The analogy

The introduction was planned by means of an analogy, because of several expected benefits. For instance, it was expected that in this way pupils would not object against the model, because previous analogies had also been worthwhile and because, in this way, it was not suggested that a gas might really be a collection of such moving and spherical particles. In addition, it was expected that the analogy would less focus pupils' attention on their own knowledge about either tiny bits or molecules.

Question:

To what extent did these benefits indeed occur?

Outcome:

This question is quite difficult to answer. It cannot be estimated whether pupils indeed refrained from objecting to the new comparison because previous comparisons had been worthwhile or because, in this way, it was not suggested that a gas might really be a collection of such moving and spherical particles. During subsequent activities and during the final interviews, it did became clear that, at the beginning of the sequence, eight pupils indeed thought that these balls did not exist or at least were not quite sure about it. However whether this initial attitude helped them to accept the model cannot be verified.

In addition, it was expected that the analogy would less focus pupils' attention on their own knowledge about either tiny bits or molecules. From the previous answers it cannot be derived whether pupils considered the little balls to be tiny macroscopic bits of air. Words like "bounce", "bang bang" and "hitting" do point at an emphasis on movement and collisions, instead of macroscopic properties such as "pushing" or "wanting to spread out", but such words were less used during subsequent activities (cf.section 5.3.2). Moreover, the use of words that refer to collisions seem to be much more a consequence of the model itself, rather than of the analogy as such. Finally, in the interviews only three pupils indicated to have immediately compared the balls to molecules. This, however, did not seem to restrain them, during subsequent lessons, from seriously thinking through alternative hypotheses, nor from reflecting on experiences that influenced their degree of belief in the existence of these particles.

5.3.3 The initial application of the model

Whereas the model was intended to be used to explain a more general regularity in the behaviour of gases, in the previous activity, it was in fact only used to gain an additional explanation for one specific phenomenon. In this section it is analysed whether pupils' subsequent applications did involve more general regularities. During these subsequent applications, pupils were expected to come to find the model involving moving particles increasingly useful. To this end, it was chosen to introduce the model in the context of coming to a better understanding of known regularities in the behaviour of gases, because it was expected that collisions, and thus movement of the balls, would be very useful to pupils in this respect. Therefore, it is also investigated to what extent collisions were important in pupils' subsequent explanations.

Question:
How did pupils use the model in subsequent explanations?

Outcome:
Pupils' application of the model in the first item of activity 4, still seemed to serve as an additional explanation for the phenomenon. Applications in subsequent items did seem to refer to more general regularities. Furthermore, in many of these explanations, the role of collisions was smaller than expected.

Illustration of the outcome:
After the third activity each group started to pose and answer questions about known behaviour of gases. This activity was guided by means of a worksheet (cf.appendix A). The following are examples of the results of each group.
Item 1:

Fr: Why is the pressure of air bigger? There are more balls in the air than in the water. So there are more balls that push against the cardboard from below than from above.
Vs: Why is the pressure of the air bigger than [the pressure] of the water? The balls collide against the cardboard, but many more balls collide against the cardboard from below than from within the glass.
An: Why is the air pressure bigger than the water pressure? Air contains more balls than water.

Item 2:

Fr: How can that be, that the pressure increases? When there is more air? More balls are pumped inside, therefore more balls move criss-cross and collide against the side.
Vs: Why? Three times as many balls is three times as much pressure.
An: Why does the pressure increase when the amount increases? Just as much air is added, so just as many balls that can push.

Item 3:

Bo: Why does the pressure increase? The same amount of balls push against a smaller area, collide more often against the wall.
Jen: Why? In a space three times as small there are the same amount of balls so [they] collide three times more often.
Al: Why? Just as many balls remain but now they have to move on a smaller part. So more collisions occur.

Item 4:

Bo: Why does the pressure increase? The balls are going to move faster because of the higher temperature. You also walk fast on hot sand, otherwise you burn your feet.
Jen: Why? When it becomes warmer the balls expand.
Al: Why? The warmer the balls the more actively they bounce.

Concerning this first item of the worksheet, most pupils had difficulties in finding a further question which they could not answer without making use of the model. The question that

was finally framed by each group, as well as the subsequent answer, differ from the expectations that were expressed in section 4.3.3, and clearly refer to the specific experiment. Pupils most likely were able to answer this question at a macroscopic level. Their application of the model thus seems to serve as an additional explanation. The answers of subsequent items were more in agreement with the expectations (cf. section 4.3.3). In retrospect, it seems that the latter items, as compared to the first one, more clearly refer to a previously established generalisation. And it may well be that, at a macroscopic level, pupils indeed could not further explain these laws. However, their written questions in these items are not sufficiently specified in order to verify this hypothesis.
The results of application of the model in the first item mainly indicate an explanation of pressure difference in terms of numbers of particles, similar to the answers in the second item. This is understandable, at this stage, since pupils' attention has not yet been focused on the possibility of differences in speed. However, the absence of the latter focus seems to have led pupils to the unexpected conclusion that water contains less balls than air. When the teacher, in a class discussion, asked about the origin of the pressure, some pupils were able to explain that the balls exerted a force by "kicking", "hitting", or "bouncing". However, concerning the first and second item, only four out of ten pupils used words such as "collide", "bounce", "hit" or "collision" in one of their final answers, and none in both. Most pupils used the word "push" (e.g., the answer of *Fr* in item 1 and that of *An* in item 2), but it often remained unclear whether or not this push originated from collisions. Sometimes the word "push" was not even used (e.g., the answer of *An* in item 1 and that of *Vs* in item 2). Concerning final answers of the third item, most pupils did refer to collisions and those who did not either had done so before and/or did use such words in their reports. However, sometimes these answers were initially less clear. The next fragment, in which the phenomenon of the third item is discussed, shows that it was quite difficult to encourage one group of pupils to give a more detailed explanation.

(2:2.5) [R= researcher]

R: Why?
Al: Well, because there are more [balls] in a smaller space.
An: There are not more, they are the same number.
Va: Look here you have a big.....
Al: More compared to the...
R: Yes, but, but...
Al: ...compared to the space there are more.
R: Yes...
An: But the space is too small for them.
R: Yes...
Al: How do you explain that.
Va: Look here you have a big container, there are a hundred balls [in it], [then] they can all quietly go their own way, but when you make the container half as big, then you still have those hundred balls, so they have to get much closer, so they go around, so you get...
R: Yes, they move....
Va: ...much more bumpety-bump....
R: Yes, so you get more...
Va: ...collisions and so on.
R: So you get more collisions?
Va: Yes.

Since it took some effort to induce an explanation of this mechanism, we should perhaps conclude that the role of collisions was not really essential in their explanations. This especially concerns the second item, for only one pupil referred to collisions. In this case, pupils may have used a model of tiny bits. More particles in the same space would, according to the latter model, result in more tiny bits of air pushing against the sides, resulting in more pressure. However, pupils may also have found the role of collisions simply too obvious to mention. In that case, it would seem that the model immediately helped them to understand why these generalisations are as such.

5.3.4 Discussion

In the second version of the scenario, the model was introduced sooner than in the first version, in order to motivate pupils to pose and answer more questions. Although we did not observe a clear positive influence of this rearrangement, during the second trial, pupils did seem more willing to continue. After the first item of the worksheet, which still raised discussion concerning which question should be asked, pupils seemed to be increasingly engaged in application of the model. Sometimes even to the extent that the model was already applied before the group had explicitly framed a question.

In addition it seems that the computer simulation makes the model more intelligible, but the benefits of the special way of introducing the model, namely by means of an analogy, cannot be clearly verified. Furthermore, because of the course of the second activity, the model was initially mainly used to explain the experiment in an additional way. Nevertheless, there are indications that the model appeared useful, because many of these initial explanations contained a mechanism of collisions. Seeing such a mechanism thus seemed to lead to immediate success. This result indicates that they not only arrived at a clear image of the course of the phenomenon, but implicitly also came to a better understanding of air pressure itself. However, in subsequent explanations, the role of collisions was often less clear. This result shows that pupils' attention was not sufficiently focussed on the importance of collisions in coming to a better understanding of the specific behaviour of air.

In order to improve the latter situation, the teacher should not only emphasise the role of collisions in the initial explanations, but foremost the search for answers in the direction of mechanistic explanations should become an explicit aim for pupils before the model is introduced. How such an aim could become worthwhile to pupils, is discussed in section 6.4.3.

5.4 The process of modelling

5.4.1 Introduction

In our approach to teaching and learning a particle model, pupils were expected to become involved in the process of modelling. That means that it was expected that they would apply the model that was introduced to the problems that were posed, that they would become more and more aware of the hypotheses of the model and that they would change these or add new ones. In this section it is discussed to what extent pupils' process of arriving at subsequent hypotheses fulfilled our expectations.

These hypotheses either concern connections between macroscopic variables and the model (section 5.4.2) or interactions between the balls, which determine the behaviour of the collection (section 5.4.3), and together these constitute a framework for particle explanations. During the further development towards a model of gases, liquids and solids, pupils were expected to take more responsibility for the way in which both kinds of hypotheses were adjusted or applied. That is, they needed to decide for themselves, which hypotheses should be maintained, which should be adjusted and which should be added (section 5.4.4).

5.4.2 Linking the collection of particles to the macroscopic system

In this section it is discussed to what extent pupils' process of arriving at hypotheses concerning the correspondence between the model and the macroscopic system, fulfilled our expectations. To this end, it was investigated whether the initial connections indeed were simple for pupils to establish. The intended correspondence between the temperature of a gas and the speed of the particles on the other hand was expected to raise difficulties. In section 4.4.2 it has been explained that, concerning this issue, the scenario was altered following the first trial. Therefore, the section proceeds with a more detailed discussion of relevant results of the first trial and why we decided to encourage pupils to evaluate, at an earlier stage in the process, other possible ways to connect the temperature of a gas to the model. Subsequently, it is discussed whether, during the second trial, the problem of how to connect the temperature of a gas to the model was raised in the way that was intended, and whether the subsequent evaluation of hypotheses resulted in the expected choice.

Initial implicit connections between the collection of particles and the macroscopic system

In chapter 4 it has been argued that the first connections to be established between macroscopic variables and the model, were not likely to raise any difficulties.

Question:

To what extent did pupils establish the intended implicit connections?

Outcome:

Many answers of pupils reported in section 5.3.2 (i.e. activity 3) and 5.3.3 (i.e. activity 4: item 2,3) indeed implicitly contained the expected connections. In item 2, concerning a situation in which more air is pumped into a container, all pupils spoke of more balls in connection with a larger amount of air. In item 3, concerning a situation in which the volume of an amount of air is decreased, at least eight out of ten pupils connected a smaller space/area/part with a smaller volume of air. In many answers concerning a comparison of the pressure of an amount of air in two different situations, pupils referred to more collisions, or at least to more balls that push. What is still missing is that more collisions (or more balls that push) result in a bigger total force on the wall, however this seems quite obvious. The important role of these collisions should however have been more emphasised (cf. section 5.3.4).

Connecting temperature to the speed of the particles: first trial

In the first version of the scenario, following introduction of the model, pupils were offered a worksheet in which a specific collection of balls was compared to six other collections. Two of these contained either a smaller or a larger number of balls, two had the same number but in a smaller or larger container, and the final two showed the same number in the same volume but all balls having either a smaller or larger speed. Pupils were then asked to use these drawings in order to explain Boyle's law and Gay-Lussac's law. Since pupils knew that Gay-Lussac's law only applied to a fixed amount of gas in a fixed volume, they could only use the final two drawings in their explanation of the latter. So, although they did not feel pressed to choose the intended explanation, they were not encouraged to consider other possibilities. Furthermore, pupils did not automatically establish the correspondence between the temperature of a gas and the speed of the balls in the way that was intended. For some pupils this process resulted in conceptual problems that became apparent when they discussed how the balls could come to move faster.

(1:5.1) [T=teacher]

Br: We did not really get an answer to the question how it can be that when the balls are going to move faster that the temperature becomes warm or the other way round.

The teacher asks who can say something about this issue.

Jes: I think it is the other way round. When the temperature becomes higher that those balls are going to move faster. Say that the temperature influences the speed and not the other way round.

Ma: But when you push such a ball, it also becomes warmer.

Br: (inaudible)..temperature.

T: *Na*, what did you want to say?

Na: (inaudible)...what *Ma* said. That when you push those balls, the temperature also rises.

Br: Yes, but how can that be? That is my question.

Br did not understand that the speed of the balls is to be called the "temperature of the gas" nor that asking why the temperature is raised basically is the same as why the balls come to move faster. An answer to the latter, in terms of transfer of momentum, also serves as an explanation for the former (under the assumption that the temperature of a gas corresponds to the speed of the particles). The teacher did his best to get these ideas across. He even explicitly compared this specific correspondence to the other ones, that were previously established, in order to explain the nature of it.

(1:5.1) [T=teacher]

T: (...) And then we said well the number of balls agrees with the amount, the volume with the space, well and then there was no other possibility than to say that in the model the speed, the speed of the balls in the model is the temperature in reality.

This was not a sufficient answer for *Br*. She agreed with the nature of the other relations, but could not agree with the same kind of connection between the temperature of a gas and the speed of the balls.

(1:5.2)

Br: Yes, but that makes, I mean that, it is fine with me that it is the speed of the balls, but when you, the force per area that is exerted by the balls by means of collisions, you can imagine that that is the pressure because they collide against something and that becomes sort of a force and then that is the pressure. But then I want to know why the speed of the balls becomes the temperature.

These objections even encouraged some other pupils to suggest other possible connections between the temperature and a specific variable of the model, such as:

- the direction of their circular movement, assuming that the balls are spinning;
- the magnitude of the balls;
- the mass of the balls.

These new hypotheses did not help to make *Br* change her mind and instead further increased her doubts. In addition, the teacher could not even hold on to his only argument that "there was no other possibility than to say that...", for now there also were other possibilities. In the end, *Br* and *Je* clearly stated that they still felt that the initial questions were not answered and showed that their conceptual problems prevented them from coming to an agreement with the teacher.

(1:5.7) [T=teacher]

Br: Yes, I do think that is not really an answer.
T: No, why, explain why you think that is not an answer.
Br: Because you do not, well because I, you do not know they keep moving, when the temperature....
Je: You said that because of the temperature the balls move, but you also said that because the balls move the temperature changes.
Br: Yes, exactly.
T: Yes.
Je: But it can't be both, can it?
T: No. No. Yes, yes.
Je: It can't be both.
T: No, very well, yes. So, you feel that that question is still open, why the balls keep moving, that that is really not strange, yes.
Je: That can't be because of the temperature, for the temperature is caused by the balls.

In retrospect, it is clear that these pupils did not agree to establish the correspondence between the temperature of a gas and the speed of the balls in the same way as they had done with the other connections. At least two other pupils did establish this correspondence in the intended way. Most of their expressions, like those of others, were not clear enough to make this conclusion, although others were. For instance:

(1:5.8) [T=teacher]

Fl: It is the question why you call, why you call the temperature, ehm, why when the balls are going to move faster, why you call this the temperature, that is the question.
T: Yes.
Fl: And the answer really is quite simple, because you just assume that it is, and because you just....
Je: Yes alright, but...
Fl: ...say that when the balls move faster, the temperature becomes higher.
Je: Yes, but you cannot do both, can you?

(1:6.2)

Ar: In a solid state, well they can, no I don't think..., but if they did not move there would not be any temperature, so....

The question now is whether these pupils, when they first established this relation, already considered it to be the same in nature as the previously established connections, or that the subsequent activities changed their mind. The following transcript shows that, in the first few lessons, they at least did not yet fully appreciate the relation such as they did at the end of the sequence.

(1:3.6)

Ar: Ehm, why they are going to move faster I don't know.
Fl: No.
Ar: Because it gets warmer.
Fl: Yes, because it gets warmer, therefore they are going to move faster.
Ar: Yes.
Fl: Yes, but that should not be true in this case [when a liquid changes into a gas], for I mean they do not move, or at least it does not get warmer.
Ar: Yes, but when it, when it, when a substance gets warmer, it is going to expand...
Fl: Yes.
Ar: ....so that means that the pressure becomes bigger.
Fl: Yes.
Ar: So when it gets warmer, they are going to move faster and so the pressure becomes bigger.
Fl: Yes...that's true.

This conversation did not yet include sentences such as "when the balls move faster, you call this a higher temperature" or "if they did not move faster there would not be any rise in temperature". Furthermore, they did not yet have a mechanism within the model available that could account for the increase of speed of the balls. After arriving at such a mechanism, this proved to be very useful to them. While thinking about the zero-point of absolute temperature, they asked themselves how the balls, that were laying still inside a container, could start moving again. They thought of two solutions, both based on transfer of momentum. These were written down in their reports.

Ar (HW1:5):
This can happen because there are also balls in the wall of the container. These balls, of a different substance, do not have this low temperature and are still moving. They collide against the balls of air and because of this they start to move again. Because of this the temperature rises.

Fl (HW1:5):
It can also be that air on the outside of the glass collides against the glass and that the glass passes through these vibrations because of which the balls start moving again.

Taken literally, these expressions would point at wrong connections between the model and macroscopic phenomena: "balls...have...temperature" and "air....collides against". However, considering their previous expressions, it would not be fair to interpret them as such. Instead it seems more likely that these pupils, by then, were so experienced in using the model in the intended manner, that they switched between both levels just as scientists often do when they talk, for instance, of cold particles. Moreover, it seems that the intended correspondence between the temperature of a gas and the speed of the particles, on the one hand, and an appreciation of the usefulness of the mechanism of collisions between balls of unequal speeds, on the other hand, are very much dependent.

Indications for improvement

The latter conclusion led us to believe that if pupils found the mechanism increasingly useful, they would perhaps have less and less objections against the suggestion that the connection between the temperature of a gas and the speed of the balls is the same in nature as the previously established connections. Therefore, during revision of the scenario, it was decided that the mechanism should be discussed plenary, before other situations of a temperature rise were to be investigated. After becoming familiar with the mechanism, and subsequently seeing that it could also account for other phenomena, pupils were expected to implicitly establish the intended connection in the intended way. Provided, however, that they were convinced that the temperature should not be connected to yet another variable of the model, such as the temperature, mass or volume of the particles. Therefore, the second version of the scenario encouraged pupils to evaluate these and other connections that they might suggest at an earlier stage in the process. We expected that this evaluation might lead them to conclude that connecting the temperature of a gas to the temperature of the balls is not adequate and that the balls themselves do not become heavier or bigger when the gas is heated. The following conversation, which was observed in the first trial, suggested that considering the consequences of a particular connection at extreme temperatures might help pupils in the evaluation.

(1:5.4) [T=teacher]

Fl: ....you have an area, and it touches it a tiny little bit, or you have a very big ball and you touch it, then you touch more of the area, even if it is round.

Ma: (inaudible)... when they all expand, that there are more...(inaudible)

Fl: So, when the temperature, when it gets warmer, that the balls expand...

T:	Yes.
Jes:	But then...
Fl:	....that because of that they have more power.
Jes:	...but then you would, when you would make it incredibly hot, be able to see under the microscope. When you can see those pieces of smoke too....
T:	What do you mean exactly, you would..?
Jes:	Maybe then you can see the air, when you make it so warm that it becomes so big, then maybe you can see it....

This suggestion, i.e. to consider consequences at extreme temperatures, was incorporated in the worksheet of activity 7 (cf.appendix A).

Connecting temperature to the speed of the particles: second trial

In the following analysis, it is first discussed whether the problem of how to connect the temperature of a gas to the model did emerge in the way it was intended. Subsequently, it is investigated whether the process of evaluating hypotheses resulted in the intended choice.

In activity 6 it should become clear that there are several ways to connect the temperature of a gas to the model. These possibilities should result in a content related motive for the next activities.

Question:

Did the problem of how to connect the temperature of a gas to the model emerge in the intended way and did pupils consider the next activities adequate in order to solve the problem?

Outcome:

The problem did not emerge in the intended way, because pupils did not understand all the intended possibilities and did not consider all of them equally important. Moreover, in their view the central problem was how the pressure could become bigger instead of how the temperature could be connected to the model. Consequently, they dud not consider the subsequent activities appropriate for the solution of *their* problem.

Illustration of the outcome:

The most important indication of the extent to which pupils did experience a new problem and understood this in the way it was intended, is the extent to which they themselves thought of all the possible variables of the model to which the temperature of a gas might be connected. At first sight, this appeared to be quite promising: three out of the four intended variables were mentioned during the inventory, i.e. "speed", "mass", and "diameter" of the balls. On second thought, some critical remarks should be made.

Firstly, not all pupils thought of more than one possible variable themselves. This result indicates that some pupils did not, or at least did not yet, understand that a new problem was being raised. Perhaps it would have been better if two alternatives had already been gathered from pupils' answers of the previous activities, before they were asked to think about other possible variables. This had been possible, for at least one group had already thought of both faster moving balls and bigger balls.

Secondly, the way in which the problem serves as a motive for further investigation depends on whether or not the alternatives are initially judged as realistic alternatives. For instance, one pupil who mentioned two alternatives in his report also wrote:

Ni (HW2:2):

> Temperature is a bigger speed of the balls, the pressure thus becomes bigger. Temperature can also be that the balls become bigger although this is very unlikely.

The other pupils did not indicate in their reports whether they judged their alternatives as unequal, but after the plenary inventory several did indicate that they wanted to start their investigation with the variable "speed" because they already thought this was the best one. So it seems that pupils had already picked their best choice and consequently were much more motivated to prove their choice to be right than to, instead, investigate other possibilities.

Finally, and most importantly, the variable "temperature of the balls" was not mentioned by any of the pupils, although it is the most obvious one. The fact that none of the pupils mentioned this hypothesis suggests that the new motive was not raised in the way it was intended and that this was mainly due to the scenario itself. The problem is that the scenario much more emphasised to find an explanation for the increase in pressure than to find a correspondence between the temperature of a gas and a variable of the model. The following may illustrate this:

(2:3.3) [T=teacher]

T: Would it also be possible that the temperature of the balls just becomes higher? Of the balls themselves?

Iv: Yes, of course, but that has, then you have (to ask) again what kind of effect does that have.

T: What kind of effect does that have.

Iv: You don't get a higher pressure.

T: You don't get a higher pressure, no, so you don't think that is logical? A higher temperature of the balls...

Iv: It does get higher, the temperature, but because he gets warmer you get either speed or...

T: Alright. Now what you're doing, very good *Iv*, what you're doing is actually reasoning why a specific solution would be possible or not. Let's put it with the other ones anyway, the temperature can maybe, the temperature of the balls themselves, and we're now going to find out in groups whether and which of those possibilities is the most obvious.

Compared to the other variables, the variable "temperature of the balls" is the most obvious candidate for a connection with the temperature of the gas. However, it is of no immediate use when explaining the increase in pressure during a temperature rise. This variable thus clearly differs from the "speed /mass/diameter of the balls", for the latter are less obvious but do seem to be of use when explaining the increase in pressure. Although the scenario did aim to make pupils aware of this difference during the subsequent group work, it was not anticipated that because of the difference, many pupils would not understand why they should investigate the variable "temperature of the balls" in the first place.

Subsequent activities were not adequate to fulfil the motive as it was raised, for pupils could not proceed in the way they desired. According to the scenario each group had to evaluate a different possibility, whereas all pupils wanted to start evaluating the hypothesis "speed". It seems that the latter can easily be incorporated in the scenario, after which pupils will probably not object to also investigate or explain why the other variables are not appropriate.

Since the problem of how to connect the temperature of a gas to the model did not emerge in the way it was intended, the subsequent process of evaluation of hypotheses as well as the final choice that was reached might also differ from the expectations.

Question:

How did the process of evaluation of hypotheses proceed and did it lead to the expected choice?

Outcome:

Several pupils implicitly connected the temperature of a gas to the temperature of the balls (i.e., $T \Leftrightarrow t$). They understood that this relation was inadequate to explain the pressure increase, but this did not encourage them to replace the relation by a new one. Instead, they searched for an effect of warmer balls that could explain an increase of pressure. After a difficult plenary evaluation, all pupils finally chose the variable "speed of the balls". Several pupils, however, implicitly understood this choice as a correspondence between the temperature of a gas and the temperature of the balls (i.e., $T \Leftrightarrow t$), combined with a causal relation between an increase in temperature of the balls and an increase in their speed (i.e., $t \rightarrow v$), resulting in $T \Leftrightarrow t \rightarrow v$. The following analysis will illustrate these results.

Illustration of the outcome:

Each group had to start with an evaluation of the variable "temperature of the balls" and then had to evaluate yet another variable (each group a different one). It was arranged in this way in order to ensure that each variable would be evaluated and to make sure that pupils would conclude that the temperature of a gas should not be connected to the temperature of the balls. the latter did not happen, however, at least not for all pupils. This became clear when several pupils displayed difficulties with the evaluation of the variable "temperature of the balls". They either did not understand why they had to investigate this option, or did not see how this variable could possibly be separated from others. The following fragment serves as an example. The conversation starts when Fr reads the question on the worksheet aloud.

(2:3.4) [R = researcher]

Fr: [When the balls are] three times as warm, will they collide more often against the wall? Yes. Three times as warm, then the pressure becomes three times as big, doesn't it?

Bo: Do you only need to consider the temperature or do you also need to incorporate for instance the speed?

R: No, you only consider the temperature, yes, when, it says when only, when the balls only become three times as warm, will it then, will they then collide more often?

Fr: But the pressure increases when it is heated, doesn't it?

......(somewhat later in the same conversation:)

R: ...but now you are only concerned with warmer, not with bigger, the balls are not bigger.

Fr: And the weight?

R: The weight is not heavier, you have, you should sort of imagine that you have a container [filled with] balls, and the only thing that you do is you make these balls warmer.

Fr: Mmm. Then you can consider three things, can't you, eh...

Wes: And the mass does not change, the speed does not change, nothing changes?

R: Nothing else changes, they only get warmer.

Fr: Well, then...

Wes: Nothing happens.

Fr: Yes, then they are going faster.

Bo: No.

Wes: No, for the speed stays the same....
Bo: You shouldn't consider that, the speed.
Fr: Then what should you consider? Whether they [collide with] more impact, eh more often....

This fragment shows that *Wes* and *Bo* were at least prepared to consider what the effect would be if the balls only became warmer, but not faster or heavier. For *Fr*, on the other hand, warmer balls had to collide either with more impact and/or more often, and therefore warmer balls had to also be(come) either faster, heavier or bigger. We interpret this as follows. Just as *Iv* in the previous transcript, she implicitly believed that the temperature of a gas should be connected to the temperature of the balls, and was now framing hypotheses as to what would have to happen to warmer balls in order to explain why the pressure increased during a temperature rise. This interpretation can also be extracted from the expressions of *An*, whose group previously had decided that "the warmer the balls, the more actively they bounce" (cf.section 5.3.3: *Al* in item 4).

(2:3.5) [R=researcher]
An: I think more often and with more impact.
R: And why do you think that?
An: Because they become more active anyway, don't they?
R: Yes, but that's not the point in this assignment, it's only about, you have to imagine that you have a container (filled) with balls, and that they are not going to move faster, not become bigger, not become heavier, but only warmer.
Al: And what will they do then? Will they more often...
R: Do you think they will collide more often?
(Al encouraged Va to also think about this)
An: I think that they will still collide more often when they get warmer.
R: Why do you think that?
An: I don't know. No idea.

Iv and *Vs* confirmed this interpretation in the subsequent class discussion:

(2:3.7)
Iv: Has no effect, ehm not directly, but the temperature of the balls does become higher, but that is not...
Vs: Because of that...
Iv: Because of that one of the other three possibilities happens...
Vs: Yes.
Iv: ....because of which the force becomes bigger, but not ehm the temperature in itself has no effect.

So we were wrong in our assumption that pupils' evaluation of the variable "temperature of the balls" would make them appreciate that it is not to be connected to the temperature of the gas. Moreover, at this stage of the process one can indeed coherently make this connection, as we think *Iv*, *Fr*, *An* and *Vs* do, if one holds that a rise in temperature of the balls must have an effect on some other variable of the model (speed, diameter, etc.) in order to account for more collisions or collisions with more impact and thus for an increase in pressure (cf. fig.5.3). So also for the pupils who connected the temperature of the gas to the temperature of the balls, it will have made sense to evaluate the variables "speed", "diameter" and "mass", although of course not to find out which of those variables is connected to the temperature of the gas, but in order to find out which of those must be effected by an increase of the temperature of the balls.

TEMPERATURE RISE	< = >	temperature rise of the balls ↓ higher speed / larger mass / etc. ↓ more collisions and/ or collisions with more impact
INCREASED PRESSURE	< = = = = >	increased total force per area that the balls exert by means of their collisions

Figure 5.3 $T \Leftrightarrow t \rightarrow v/m/\ldots$

The evaluation of these other three variables proceeded more or less as expected. Eventually, the variable "speed" was chosen, but the decision-making process was not always very clear. None of the groups were completely finished thinking about the wanted and unwanted consequences of the variable they evaluated (after they had evaluated the variable "temperature of the balls"), although the group that discussed the variable "speed" was almost ready at the end of the available time. Reasons for the delay were that they had had many problems with the evaluation of "temperature" (see above), or that they had not wanted to evaluate any other variable than "speed" because they already believed this was the best choice (see above), or that they actually needed more time to think about the consequences, especially in the case of the variable "diameter". But although it took them some time, the group that studied the variable "diameter", did reach the conclusion that whereas larger balls would not collide with more impact, they would collide slightly more often. Towards the end of the lesson, the teacher interrupted the group work in order to close with an inventory of the results of the various groups. Pupils then put forward, as unwanted consequences of the various variables, such things as:

- the balls cannot just become heavier; you need something to make them heavier;
- when you measure the weight of a flask (filled with air) before and after heating you would have to find a difference;
- why would the balls begin to move faster when it gets warmer "around them";
- in order to find out whether they become bigger at higher temperatures you could use a microscope;
- the balls would probably explode if you continued to raise the temperature.

Concerning the second remark, the teacher commented that experiments as proposed there were done and yielded no difference in weight. This effectively ruled out the variable "mass". At the end of the sequence, during the interviews, many pupils were still able to explain why they did not choose this option.
Following the lesson that ended with this inventory, the teacher was instructed how to build on it in the next lesson in order to prepare a decision between the remaining variables "speed" and "diameter". He was instructed to explain, first of all, that the objections "the balls cannot just become heavier; you need something to make them heavier" and "why would

the balls begin to move faster when it gets warmer around them" (you need something to make them move faster), could also have been stated for the variable "diameter": the balls cannot just become bigger; you need something to make them bigger. Therefore, so he was to continue, the decision between the variables cannot at this stage be based on objections of this kind. Subsequently, he was to remind the pupils that on independent grounds the variable "mass" had already been eliminated, and to ask whether concerning the remaining variables too there might be such additional grounds.
In the subsequent lesson the teacher did not act according to the instruction, however, and instead almost immediately asked for a decision. One pupil cleverly responded by asking whether the balls could be seen under the microscope, for then it might be possible to see whether they would begin to move faster or would become bigger. The teacher realised that this was not the discussion he ought to be involved in and, from then on, took over almost completely. He said that in the next lesson they would check whether the balls can be seen under a microscope, subsequently focused on unwanted consequences of bigger balls, and finally suggested that the balls eventually would have to become visible. The teacher did not respond to the pupil who repeated his earlier objection that the balls eventually would break, nor adequately responded to the pupil who did not accept the teacher's suggestion.
The fact that none of the pupils objected to the final choice for the variable "speed", is most likely due to their knowledge about molecules, which they had learnt in chemistry lessons. They already knew beforehand, that is, that "speed" was the right answer. In addition, they perhaps somehow intuitively considered it to be more far-fetched and less effective to assume that the balls would become bigger, without getting heavier, than to assume that their speed would increase. At the end of the sequence, during the interviews, half the pupils indicated that the variable "diameter" had been ruled out on the ground that otherwise the balls ought to become visible at high temperatures, which they do not. Others indicated that they would eventually break, that in order to become bigger they had to consist of parts, or that this assumption was less probable because bigger balls would not collide with more impact and not really more often either.

Arriving at a mechanism: second trial

The remaining objection to the chosen variable "speed", namely "why would the balls begin to move faster?" served as a motive for further investigation. As can be expected from the above analysis, it was understood in two different ways, depending on the way in which the temperature of a gas was connected to the model. Those pupils who connected this macroscopic variable to the speed of the balls in the way it was intended, namely $T \Leftrightarrow v$, understood the question as follows: "with what mechanism at the level of the model should we compare HEATING, in such a way that as a consequence of that mechanism slow moving balls will come to move faster?" (cf. fig.5.4). Those pupils who connected the macroscopic variable to the temperature of the balls, i.e. $T \Leftrightarrow t \dashrightarrow v$, implicitly imagined a similar process of heating both at macroscopic and model level, and needed to find out how warmer balls could come to move faster (cf. fig.5.5).

As can be expected these different questions lead to different attempts at solutions. Firstly, these attempts are further analysed. Secondly, it is investigated whether pupils, who initially connected the temperature of a gas to the temperature of the balls, changed their mind during subsequent activities.

LOW TEMPERATURE	<==>	low speed
HEATING ⇓		⇓ ?
HIGH TEMPERATURE	<==>	high speed

Figure 5.4 T⇔v.

Question:

Which solutions were suggested and to what extent did these give indications for the way in which the temperature of a gas was connected to the model?

Outcome:

Four different solutions were found. These are summarised in fig.5.6-9. Each will be illustrated by means of pupils' expressions.

Illustration of the outcome:

Because of lack of time at the end of the lesson, the problem of how the balls could come to move faster was not adequately introduced. Out of ten pupils seven indicated, either by means of their report or by their participation in the class discussion in the next lesson, that they had thought about the problem at home. Only three of them, *Bo*, *Ni* and *Jen*, used transfer of momentum in their solution. *Bo* did so most clearly, as e.g. appears when he tried to explain his solution during the class discussion.

(2:4.3)

Bo: Well, ehm, so the balls in the flame move with ehm, a very high speed, and the collide with ehm, a high speed against the balls of the cold air, and then the balls of the cold air are also going faster.

Fr: I don't understand.

Vs: So the heat also consists of balls?

Bo: The flame is a hot gas.

LOW TEMPERATURE	<==>	low temperature of the balls
HEATING ⇓		⇓ heating
HIGH TEMPERATURE	<==>	high temperature of the balls ⇓ ? high speed

Figure 5.5 T⇔t→v.

LOW TEMPERATURE	< = = >	low speed
HEATING ⇓		⇓ collisions with faster moving balls of the flame, as a result of which slow balls move faster (i.e., transfer of momentum)
HIGH TEMPERATURE	< = = >	high speed

Figure 5.6 Transfer of momentum within T⇔v.

This explanation of *Bo* is one of several examples that show that he considered the transfer of momentum as a helpful mechanism to account for a rise in temperature of the gas. He therefore did not need to consider warm and cold balls and thus clearly used the framework of fig.5.4 and 5.6 (i.e. T⇔v). The other two pupils who thought of a similar solution, *Jen* and *Ni*, sometimes still used "warm/cold balls", quite likely as a substitute for warm and cold air (i.e. fig.5.6: T⇔v), but perhaps because they still believed that the balls themselves would also (in a parallel process) become warm/cold (i.e. fig.5.8: T⇔v,t).

Jen (HW2:3):
The balls of the flame have a higher speed, because these bounce with a high speed against the air ball(s) they also begin to move fast. [above "they also begin" she wrote: +pass through heat]

The solution of *Bo* almost immediately raised the problems that were expected.
(2:4.4) [T=teacher]

Wes: But then you still have a problem.
T: *Wes*, you still have a problem.
Wes: For if you...put the air in a specific flask, or such a syringe and you seal it, and you connect it to a pressure meter, and you heat it, then the pressure also increases and the balls do not touch each other because the glass is in between.

LOW TEMPERATURE	< = = >	low speed
HEATING ⇓		⇓ in the hot environment the slow balls (absorb and) change heat into energy or motion, as a result of which they move faster
HIGH TEMPERATURE	< = = >	high speed

Figure 5.7 Change into energy/motion within T⇔v.

LOW TEMPERATURE	<==>	low speed and low temperature of the balls	
HEATING $\Downarrow$		$\Downarrow$	collisions with faster moving balls of the flame that are also warmer, as a result of which slow balls move faster and become warmer (i.e. transfer of momentum and heat)
HIGH TEMPERATURE	<==>	high speed and high temperature of the balls	

Figure 5.8 Transfer of momentum and heat within $T \Leftrightarrow v,t$.

The fact that *Wes* immediately raised this problem after *Bo* explained his solution indicates that he understood this mechanism quite well. Furthermore, since he did not reject the solution in itself, his interpretation of the correspondence probably agreed with either $T \Leftrightarrow v$ or $T \Leftrightarrow v,t$. The other expected problem was put forward by *Al.*

(2:4.5) [T=teacher]

Al: But then how does the first ball become, how is the first ball going faster?

T: Very good. How is the first ball going faster? How for heaven's sake does this ball get that speed?

Al raised this question because *Bo*'s solution did not account for the higher speed of the balls of the flame. It appeared that she believed that her own solution did, but she did not get the chance to explain it. In her homework she wrote:

Al (HW2:3):

The balls change the heat into energy by means of which they are going to move faster, because of which the air becomes warmer. Also because the balls spread the heat. (friction)

This solution explains why air becomes warmer, but it could probably also account for the high speed of the balls of the flame themselves. Since *Al* previously stated that the balls themselves did not get warm, which she repeated during subsequent activities, it seems she believed that heat did not increase the temperature of the balls, but instead caused them to move faster by transferring energy to them (i.e. fig.5.7). Another pupil of her group, who also decided the balls themselves did not get warmer, put forward a similar explanation:

(2:4.5) [T=teacher]

Va: I think the balls change the heat into motion.

T: Change heat into motion, yes, but where does the heat come from?

Va: From the flame.

T: From the flame, yes but we just said that the flame itself is, that flame itself is ehm heat and the balls....

Va: Well the balls take, they absorb the heat of the flame and change it into motion.

T: Yes, but how do they absorb, do they absorb it by mutual collisions?

Va: How do I know how they absorb, I'm not there to see it.

LOW TEMPERATURE	<==>	low temperature of the balls
HEATING $\Downarrow$		$\Downarrow$ heating (i.e. heat transfer during collisions)
HIGH TEMPERATURE	<==>	high temperature of the balls
		$\Downarrow$ change heat into energy
		high speed

Figure 5.9 Change into energy within $T \Leftrightarrow t \rightarrow v$.

Both pupils could not give a detailed mechanism to explain how heat changes into motion, however. Two other pupils clearly believed that they had to find out how warmer balls could begin to move faster (i.e. fig.5.5 and 5.9: $T \Leftrightarrow t \rightarrow v$). They wrote in their homework:

Vs (HW2:3):

because the balls become warm, the combustion goes faster, and so a lot of energy emerges, because of the energy they can go much faster.

An (HW2:3):

The balls that represent the air more and more touch the balls that represent the flame, the longer the air balls are heated by means of the flame balls, by means of which the heat is changed into energy, because of which they are going to move faster.

Vs explicitly mentioned that the balls became warm, which agrees with his earlier statements (cf. 2:3.7). *An*'s expressions were less clear, but she did believe the balls themselves would become warmer, as she showed during a subsequent activity.

(2:4.8) [T=teacher]

Al:	No, those balls are not hot.
T:	They are heated by the flame, aren't they?
An:	Yes, you see, I was right.
Al:	So they are hot?! And we just said....
T:	Of course.
Al:	...that when the temperature becomes warmer, the balls do not get warmer.
T:	No the balls are not warmer, no no no, the balls get, they have a....
An:	They already have heat.
T:	No they don't have heat.
Al:	They are only faster.

During the class discussion, not all four solutions presented above were put forward. In fact, only the solution suggested by *Bo* was discussed. This was mostly due to the way in which the discussion was directed by the teacher. As the scenario had not sufficiently anticipated other solutions, the teacher most likely was less sensitive to indications of these solutions in pupils' responses to the solution suggested by *Bo*. Because no other solutions were discussed, all pupils were more or less forced to solve the subsequent more difficult problems of temperature rise by means of the mechanism that was put forward by *Bo*. It was expected that, during these further applications, pupils' ideas about how to connect the temperature of a gas to the collection of balls would gradually become more in line with the intended model.

Question:

Did pupils change their hypothesis?

Outcome:

Many pupils seem to have changed their hypothesis. At the end of the sequence seven pupils (*Al*, *Wi*, *Ni*, *Jen*, *Wes*, *Vs*, *Bo*) showed that they interpreted the connection between temperature and speed as intended, i.e. T⇔v (fig.5.6). In addition, one pupil (*Fr*) said that, during the increase in speed, the balls also became warmer, indicating T⇔v,t (fig.5.8). The pupil who missed the lesson concerning the mechanism of transfer of momentum (*Iv*) still believed that the balls would get warmer and that because of the rise in temperature they would somehow gain speed, thus T⇔t→v (fig.5.9). The remaining two pupils were not sufficiently clear in their expressions. One of them (*Va*) seems to fit in the first category but may also belong to the second, the other (*An*) in the second or the third.

Illustration of the outcome:

The following discussion will first show pupils' solutions to the more difficult situations of temperature rise. Subsequently, three examples of a switch from one explanatory framework to another will be discussed, and finally we will illustrate the lack of progress of *Iv*.

All pupils were asked to use the solution of *Bo* to explain the more difficult situations of temperature rise, which could be characterised as caused by either heat or work performed on the system. During subsequent class discussion, solutions were expressed by *Bo*, *Jen*, *Al* and *Va*. The latter pupils had previously already shown that they either considered T⇔v or T⇔v,t. The solutions were all as expected. The following two serve as examples.

Bo (WS2:4.3):

At high speed you push the ball away, because of which the ball moves faster (just like tennis).

Al (WS2:4.1):

The balls outside move very fast against the glass. The glass is then also going to move a bit and makes the slow balls move.

Most of the final interpretations were gathered from the interviews. In order to illustrate a case in which pupils seem to have switched from possibly T⇔v,t to T⇔v, expressions of *Ni* and *Jen* are selected. Although *Ni* and *Jen* were both able to figure out the mechanism of transfer of momentum by themselves, they initially kept talking of warm and cold balls. During the interviews they clearly stated that the balls themselves did not become warmer.

(int.Jen/Wes)[R=researcher]

Jen: (....) the stuff that's hot, by means of which you heat it, that has, the balls that are in there, already has a faster, a higher speed and when they touch the slow balls, that influences one another and then they're also going to move faster.

R: Mmm. Yes. And when the temperature is higher, do the balls also get warmer?

Jen: (shakes her head) Only faster.

(int.Ni/Bo)

R: (..) but how are they going to move faster, how can that be?

Ni: How that can be. Because they are pushed by the balls ehm that are already warmer, thus those that already have a higher speed. Then those balls are pushed and then they're going to move faster.

R: (...) Are the balls also warm themselves?

Ni: No.

Bo: They don't have to.

Ni: It would be possible.

Bo: Maybe it could, but ....

Ni: If they also consist of balls, these balls, and those balls are also going to move faster, then it would be possible that they...

Bo: But in itself it's not really important, whether warm or cold, whether the temperature differs.

R: Yes, for?

Bo: Yes, it doesn't change, in itself, it doesn't change the speed.

The following fragments illustrate a switch of framework from $T \Leftrightarrow t \rightarrow v$ towards $T \Leftrightarrow v$. During activity 10, *Vs* initially tried to explain to *Jen* how warmer balls would gain speed.

(2:4.7)

Vs: Look here, you know combustion, from biology?

Jen: Ehm...

Vs: And then they make energy, you see because of that heat the combustion goes faster and then they make more energy, then they can go faster.

Jen: Which combustion? What do they burn?

Vs: You know, from biology, combustion....

Jen: What combustion?

Vs: Yes, it is slightly different here, but well....

Jen laughs.

Vs: ...because it gets hot the combustion just goes faster.

Jen: And then they have too much energy and then they are going to move faster?

Vs: Then they make more energy and then they go faster.

Jen laughs again.

But this was not accepted by *Jen* who either already considered $T \Leftrightarrow v$, or at least $T \Leftrightarrow v,t$. She subsequently applied her explanation to the new situation. This was not only well understood by *Vs*, but he also considered it a much better solution.

(2:4.7) [R=researcher]

Jen: Oh, I know what they're doing. (...) The faster balls in the glass of the water, they bounce like this against the glass, and the glass is also going to move a bit like this, and then ehm, then the glass collides, for that becomes (inaudible) and then at the same time against balls and then it is going to move a bit faster and then they touch all the other balls...

Vs: Yes...

Jen: ...faster and faster...

Vs: ...all the balls from the outside are going (to collide) very fast against the glass, and because of this big collision it goes a bit like this....

R: Yes...

Vs: ...because of the collision.

Jen: We don't see it but it does happen.

Vs: When a slow ball arrives here, then it goes like this, that one goes "wham" that one also goes faster.

Jen: Don't you agree?

R: I think, it seems quite...

Vs: Don't you agree? I think it's great.

Jen: Yes so do I.

During the final interview, *Vs* showed that his interpretation had indeed changed towards $T \Leftrightarrow v$.

(int.Vs/Al) [R = researcher]

Vs: That's really the air around them, that is ehm, that is warm, but the balls themselves not really.
R: And what do you mean by the air around them? Is there, is there air around the balls?
Vs: No, so not really. But that's really, that's really nothing, just vacuum, but so that's warm or cold.
Al: But that's because when you...
R: So vacuum can be warm or cold?
Vs: (laughs) Well, yes, in that theory...
Al: No, but that's because, when you heat something it becomes warmer, so you also think that, when you heat a liquid, that those balls become warmer, that's what you say then, but you do know that they're going to move faster.
Vs: But in itself it would be possible that those balls become warm or cold, for it does not have any effect anyway.

A third switch is illustrated by expressions of *Fr*. Her previous expressions seemed to point at the relation $T \Leftrightarrow t \rightarrow v$. At the end of the second part of the sequence, her expressions more closely resembled the intended framework:

Fr (WS2:4.1):

Balls can go faster or slower. Slower when the balls of the object next to it move less fast (so when the object is colder). Faster when the object next to it the balls of which move faster. The object next to it then is warmer.

She seemed to have adopted $T \Leftrightarrow v$, but during the final interview she added that the balls themselves also became warmer, indicating $T \Leftrightarrow v,t$.

(int.Fr/Wi) [R = researcher]

Fr: The speed of the balls indicates the state, ehm, and the speed of the balls also the temperature. Ehm. Balls can pass through speed to other balls of another substance. (....) Heat means that something moves faster. (...) The surrounding air does not get warmer, so then the balls have to get warmer.
R: Which surrounding air?
Fr: Ehm, nothing. I said air, but it is just nothing. Yes, the balls do get warmer, I do think so, yes.

Iv had not changed his mind, probably because he missed the activities concerning transfer of momentum. During the final interview he was not really able to explain how warmer balls could move faster.

(Int.Iv) [R = researcher]

R: How can they move faster?
Iv: Well, because of the temperature, then they get more energy so to say, added in ehm.. That's what we learnt previously, with heat and energy, that they when you, heat just consists of transfer of energy, so ehm, and then they get more energy so to say, because of which they can go faster or something like that. In any case it is because of the temperature.
R: It is because of the temperature, but, I find that very hard to imagine. How, how, why are they going faster all of a sudden? How do they get energy?
Iv: Well I don't know. Probably I missed a lesson or so. No I don't know. Let's see, how can that happen. (15 to 20 seconds of silence) Well, I don't know.
R: No idea? You didn't think about this before?
Iv: Yes, I did, but it's a bit difficult, I left it like that. I thought that's something we assume, like so many things that we assume, so I thought well that's something you just assume. With that, if you don't assume that, then you cannot explain it, so if you do assume that, then you can make that model and then you can explain everything. So it would be logical.

Discussion

Compared to the first trial, the second version of the scenario is a considerable improvement, for more pupils indicated that they finally considered T⇔v. The analysis of the process during the second trial points at an important mistake in our expectations, namely we expected that pupils would no longer connect the temperature of a gas to the temperature of the balls once they realised that this correspondence was not sufficient to explain Gay-Lussac's law. Fortunately, this mistake did not have a negative influence on the course of subsequent activities, for also in the framework T⇔t, a new (but unexpected) motive emerged.

Furthermore, the analysis shows that the choice between variables which was supposed to be made at the end of activity 8, could not yet be made. Just as in the first trial, there was initially too much emphasis on establishing the correspondence between speed of the particles and temperature, as such. Arriving at this hypothesis should take place in a larger context of reflection on system/surroundings, heating/cooling, and perhaps even the zero-point of absolute temperature. In such a context, a final evaluation of which variable of the model is to be connected to the temperature of the gas, should not be performed until complete frameworks, such as those of fig. 5.6-9, can be compared. As a result it becomes clear that a really plausible mechanism to account for t-→v cannot be found, whereas transfer of momentum indeed serves as a convincing way to account for v_{low}-→v_{high} . It then no longer seems important whether pupils consider T⇔v or T⇔v,t as long as they do not use the temperature of the balls in their explanations of heat transfer. The process of teaching and learning this particle model would become much clearer to both pupils and teacher if these frameworks were made explicit. In fact, it might even contribute to the evaluation of other variables such as the "diameter of the balls". The following transcript serves as an example that the availability of a plausible mechanism for the one case but not the other, could also contribute to a final choice between "speed" and "diameter".

(int. Wes/Jen) [R = researcher]

Wes: I think, whatever you're doing, you just always have to ehm draw a conclusion that it has to do with the speed. For, or ehm, you can't say the mass changes or ehm their diameter changes or something else, for that doesn't really explain it. I mean you can't say well how are those balls going to get bigger. If you for instance put water in ehm, such a flask and that in hot water, then you can't say well the balls of hot water already are somewhat bigger so they're going to enlarge the others. That's not very plausible.

R: No, and with speed it was plausible?

Wes: Yes. You just know that when something fast bounces against something slow and it is such a rubber-ball-effect, then you know that the other one is also going to move faster. And that's how it goes on and on.

5.4.3 Additional hypotheses about the behaviour of the particles

Initial assumptions concerning the behaviour of the particles were put forward when the model was presented, namely the ongoing movement (rather implicitly) in straight lines, and collisions against the wall and other balls (more explicitly by means of the computer simulation). Pupils did not explicitly frame these assumptions themselves, but section 5.3.3 showed that they were indeed able to imagine the consequences of these assumptions on the behaviour of the balls in specific situations. The hypothesis that the balls themselves do not change, was added to the model by means of reflection on pupils' own explanations, and will therefore be discussed in section 5.5.2.

Subsequent hypotheses were expected to be framed to solve a new problem, namely how the balls can keep moving. In this section it is discussed whether this motive was raised and whether all pupils did agree to add the new hypotheses, concerning empty space between the balls and perfect collisions, to the model. In addition, it is summarised which other problems concerning the behaviour of the particles were raised.

A good reason for an unusual assumption

Following the observation of a mechanical simulation of moving balls, a new question about the ongoing movement of the balls was expected to be raised.

Question:

Did the problem of how the balls can keep moving emerge and did pupils consider the subsequent activity adequate in order to solve the problem?

Outcome:

During the first trial, this problem was more or less raised immediately after the introduction of the model, because the latter was presented by means of a mechanical simulation. The solution to this problem had to be postponed, as it was expected that pupils would not yet be ready to assume "strange" hypotheses such as empty space between the balls and perfect collisions. During the second trial, the same mechanical simulation was successfully used in order to raise the same problem at a later stage. One pupil even partly solved the problem immediately after the mechanical simulation was demonstrated by referring to empty space between the balls, "because of which they always keep going". The subsequent worksheet, in which pupils were asked to design a mechanical simulation themselves, did not raise any difficulties and resulted in the expected outcomes.

Not all pupils worked on the problem of how the balls can keep moving themselves. Since, in the science educational research literature, arriving at the hypothesis of empty space is often considered to be rather problematic, it may be that pupils will not arrive at this assumption when they only hear it from others without having thoroughly investigated the problem themselves.

Question:

Did all pupils agree to add the new assumptions, concerning empty space between the balls and perfect collisions, to the model?

Outcome:

During the first trial, none of the pupils objected to perfect collisions, and only one had difficulties in accepting the hypothesis of empty space between the balls. Because of the latter result, the scenario was slightly changed. During the second trial no objections were put forward against empty space, but perfect collisions were less easily accepted. The objections against the latter indicate conceptual problems that became more apparent in subsequent lessons (cf.section 5.4.4).

Illustration of the outcome:

The specific pupil in the first trial mentioned above, did not make any objections when the hypotheses were put forward in the class discussion about the simulation that was sketched in the worksheet. It was only after it was assumed that the space between the balls of liquids was also empty, that she realised that she did not agree. When she was asked why she had not objected before, she explained that she had not realised that they really assumed that there was empty space between the balls. She thought that the balls were only compared to rubber balls and the space between the balls was only compared to empty space. And, since she believed that the balls were not really rubber balls, she also believed the space was not really empty space.

Because all but one pupil did agree to add the intended hypotheses to the model, it was decided that no major revision of the scenario was necessary. The worksheet itself was hardly changed, but the teacher was asked to emphasise, during subsequent discussion, that the ongoing motion forced them to make new hypotheses about the balls. In other words, arriving at the most appropriate simulation as such, also had consequences for the model. Furthermore, in the improved scenario, pupils had already concluded that the balls themselves not only have a fixed mass and magnitude, but also that the balls do not have (to have) a temperature and do not change in any other way than in their speed and position. Therefore, they were expected to be more ready to make the next "strange" assumption, provided that there were good reasons for it.

The pupils who participated in the second trial indeed all incorporated the hypothesis of empty space in their model. Only one pupil needed an additional argument to be convinced of its necessity, namely that there couldn't be air between the balls for the balls themselves were the air. However, this time the hypothesis of perfect collisions was questioned. The first doubts that were expressed may originate from pupils' experiences in daily life.

(2:7.1) [T=teacher]

Ni:	Is that really possible, that you, that you bounce and there ehm, and there's no loss of speed?
T:	Yes, is that really possible, you may ask yourself, right. But what, what ehm, what do we thus need to assume about the balls?
Ni:	Well, that it ehm, that it thus ehm...
?	Super-bouncing-balls.
Ni:	...that they do not slow down.
T:	That they do not slow down and that there's no loss of speed. So that with ehm, that is something that in daily life, daily life you don't see, in daily life everything you encounter slows down, but if we....
Ni:	That's probably caused by the balls.
?:	Yes.
T:	Maybe so.

(2:7.2)

Wi:	But when they collide against another ball then they much, they slow down, don't they?
T:	And that just was the group of ehm, the questions that they ehm, the problem that they dealt with, that they found that well if they, if they collide then they thus have to collide in such a way that... well what you just said...
Ni:	That there's no loss of speed.
T:	That there's no loss of speed.

The macroscopic objects that pupils had seen colliding before probably did not perform perfect collisions. In that respect, the teacher appears to answer quite adequately. However, in subsequent conversations, pupils showed that the objections much more referred to the assumption that the balls are not slowed down *in spite of the existence of an attractive force that is exerted on them.*

(2:7.3) [T=teacher]

Iv: So ehm, in my opinion if you let something bounce in a vacuum space then it will continue much longer, probably, if there is no...
Ni: Then it'll never stop.
Iv: ....if you are not bothered by the gravitational force.
T: What? What was that with vacuum and not bothered by gravitational force?
Iv: Yes if you were not bothered by the gravitational force, it would continue to bounce much longer.
T: But was that vacuum? Is that vacuum? What did we see with air, that, vacuum did that have anything to do with gravitational force?
Iv: No but...
T: Were things going to float in, were things going to float in vacuum? No. That's something completely different.
Iv: No, that's what I just said. I don't say it's like that. But I say if it were like that then they would indeed, in my opinion, be able to bounce endlessly, without gravitational force.
Ni: With gravitational force too.
Iv: Yes, do you think so?
Ni: Yes they have to, for otherwise....
Iv: (inaudible)
Ni: ....otherwise those balls here would stop too, wouldn't they.
Iv: Yes but they're not much bothered by it, or something.

In this case it was the gravitational force that, according to *Iv*, slowed down balls that moved upward. It appears that *Ni* had, by then, taken over the argumentation of the teacher, whereas *Iv* could only agree should the balls be "not much bothered" by the gravitational force. In other words: if the force hardly acted on them. Section 5.4.4, however, will show that *Ni* was not convinced either, and that their objections not only concerned the gravitational force but also mutual attraction.

The teacher did not really address *Iv*'s conceptual difficulties. He could have pointed out that the balls were not only slowed down when they moved upward, but also accelerated when they moved towards the earth. And that, since the attractive force did not change, the acceleration would be just as large as the slowing down. In other words, in effect there would be no loss of speed. Even though pupils might still have found the assumption of perfect collisions difficult to imagine, their major objections may have been taken away by such an argumentation. Instead, the teacher only told the pupils that they had to make the assumption in order to account for the ongoing movement of the balls.

Other questions about the behaviour of the balls

Besides the question of how the balls can keep moving, some other questions about the behaviour of the balls were put forward. The questions that were gathered plenary in activity 15 concerned the volume and speed of the balls, how many there were in a cubic centimeter, whether different substances consisted of different balls and whether they were attracted by the gravitational force. In the next activity, the speed of the balls was calculated, differences between balls of different substances were reflected upon and the number of balls in a cubic meter was presented. However, in this activity, pupils themselves were not able to imagine how to proceed in order to solve these problems. Furthermore, several pupils did not find these questions and solutions very interesting.

5.4.4 Further development towards a model of gases, liquids and solids

In the final part of the approach, pupils were expected to further develop the model in such a way that it also accounts for known behaviour of solids and liquids. In this section it is discussed which hypotheses were added in particular situations. Since in section 4.4.4 doubts were expressed whether pupils would want to continue applying and adjusting the model long enough, it is also discussed here under which circumstances they were indeed challenged to do so.

Choices concerning previous and new hypotheses

In section 5.2.3, pupils' final models have been summarised and it has been discussed to what extent these agreed with the previously developed framework. The process of development towards these final models can be divided in two stages, namely initial adjustments during their participation in activity 19, and further refinement during activity 20. In this section, these stages of the process will be illustrated.

Question:
Which choices were made initially and which during further refinement?

Outcome:
Pupils' conversations during initial adjustments show that invariance of the balls, as well as their ongoing movement, served as principles that did not need to be adjusted. In addition, one group initially only suggested differences in configuration, whereas the other two groups immediately connected macroscopic solidity to an attractive force between the balls. Their conversations also show that one of these groups did not see how they could combine their new assumption about mutual attraction with the old hypothesis of perfect collisions. At a later stage, both groups decided that the magnitude of the attractive force between the balls was not identical for each substance. One group even explained how this could be the case and, probably because of their difficulties with the assumption of perfect collisions, framed additional hypotheses concerning the movement of the balls.

Illustration of the outcome:
Without strictly following the steps of the worksheet, pupils started to adjust the model in order to account for the differences between gases, liquids and solids. One group initially only considered differences in mutual distances.

(2:7.14) [T=teacher]

Al: Well, we've already imagined that with ehm, with liq, ehm with gases the balls are far apart, with liquids they're somewhat closer and with solids that they're even closer together, so that it is even more (inaudible).
T: Yes?
Al: Well, that's where we were.
T: Alright, so that's your ehm, that's your model then. Not yet?
Va: Not completely no.
Al: That's just an idea.

As discussed in section 5.2.3, this fragment again indicates that pupils' appreciation of the relative size of mutual distances was inappropriate. The two other groups immediately incorporated an attractive force in their model. Their conversations show a strong connection between the state of the substance and the speed of the particles (cf. section 5.2.3).

(2:7.9)

Bo: Those balls they attract each other, they also really attract each other. With ehm a solid and a liquid they have a lower speed and then they're also really held together. Ehm, gas they really have a high speed, and so they can just really ehm move. That's why they also spread out. And well, a liquid does spread out too, that goes a bit faster than ehm a solid, so it does spread out, it doesn't go all ehm far away and a solid those things are, balls are just so slowly, they attract each other, yes those ehm just stay the same.

(...)

Fr: With a gas the balls move fast, because of which they can quickly free themselves from other balls.

Bo: Because of which they can pull themselves loose, tear themselves loose from that attractive force.

Wes: Because of which they are less attracted by other balls.

Bo: Then they're just going so fast that they can hardly be attracted.

(2:7.12) [T=teacher]

Iv: That is the same as when you have two magnets, and you have, the one magnet, you know it attracts, if you throw it fastly near the other, then it has, then it does pass you know, but if you do it slowly, then it is stuck. [The latter is illustrated by means of a sound that refers to a collision.]

T: Yes, that sounds very good, sounds very good.

Ni: But then we still have one problem, for that is of course, if they move very fast, whether they then, then it would really slow down a little.

T: Whether they then...?

Ni: Then they would indeed slow down a little, by, because they do have an attractive force towards each other. Then they may move very fast, but they will slow down anyway.

The latter fragment indicates that both *Iv* and *Ni* still seemed to have difficulties with combining the assumption of an attractive force with the assumption of perfect collisions (also cf.section 5.4.3). The teacher did not further discuss this problem. During the conference, when the final models were compared, this problem became a major issue (see below).

Other applications did lead to further adjustments, e.g. the assumption that the magnitude of the attractive force between the balls was not identical for each substance.

(2:8.2) [T=teacher]

Wes: Boiling point and melting point has something to do with the attractive force, right?

Bo: Yes ehm what-d'you-call-it, how....

Fr: That the one ball goes faster than the other, that it goes faster more quickly.

T: Yes, that's what *Al* said too but I just asked, how can that happen? *Al* asked.

Al: Because the attractive force between the balls is smaller.

Fr: Then the attractive force is bigger or smaller.

T: Seems a reasonable remark, right? And when do you have a smaller attractive force?

Wes: When you have a lower boiling point and a ehm, or a lower melting point.

Al: When the boiling point is high...

T: Sounds reasonable, right?

Al: ...ehm, boiling point low, is high, is high, so then you need a lot of heat so then the attractive force is big.

The other group also discussed why attractive forces between balls of one substance were bigger than between those of another substance.

(2:8.4) [R=researcher]

Ni: ...and with the bigger balls the attractive forces on each other are bigger...

Vs: Exactly.

Ni: ...so it has a higher boiling point for it is more difficult....

R: Yes, that I don't understand yet, what, yes...
Vs: Yes, well look, when the balls are bigger....
R: ...the forces are bigger...?
Vs: ...then the attractive force is bigger and then they also stay closer together more easily because they are bigger, then it longer stays a liquid, then it takes longer before they are apart and become gas.
R: Because the attractive forces are bigger?
Iv: Because they're bigger again.
Vs: They also stay...
R: And because they're bigger again.
Vs: These two balls stay together more easily than these two balls.
Ni: No.
Vs: Can [go/be] much further apart.
Iv: In the same space.
Vs: Yes here, these go away from each other more easily than these, these can't....
R: Why? Why is that? Why do bigger ones have a bigger attractive force?
Ni: That's just the way it is..
Vs: Yes.
Iv: That's what we in physics....
Ni: Two planets also have a very big attractive force on each other, don't they...
Vs: That too, but you shouldn't add everything that...
Ni: ...and *Jen* and I also have an attractive force on each other.
Iv: Yes and I and *Jen* too.
(They all laugh)

Gradually, the ideas of this group about interactions between balls changed, probably because of their problems concerning perfect collisions and attractive forces. When they were asked to explain why the balls would move further apart if they moved faster, one pupil put forward a detailed description of the way in which balls of liquids moved. This was easily accepted by the rest of the group.

(2:8.5) [R=researcher]
Ni: No, look, look those balls sort of turn around each other....
R: Yes?
Ni: ....they turn around each other.
R: They turn around each other is what *Ni* says.
Jen: Yes.
Ni: Yes. And they have such a, such speed that they don't...
Jen: That they can't go through.
Ni: ....collide against each other.
R: No...?
Ni: So this is a ball and it keeps spinning around....
R: Yes...
Ni: And it has such a speed that it is not attracted. The distance in between stays the same all the time, if the temperature is the same. If the temperature becomes bigger, then it is going to move faster and faster...
Vs: Then it goes a bit further apart.
Ni: ...but it can't bounce against this so then it has to, then it has to slightly, has to make a bigger curve around it. So then it's going to move ever faster, and this one too...
R: It sort of goes off the curve, because it has a higher speed it goes off the curve?
Ni: Yes. But it doesn't really go off the curve, he stays in a path around it. But when it is a gas, it does go off the curve.
R: Yes, I see.
Ni: Then there's no attractive force on each other any more.
Vs: Alright *Ni* !!

Further application and adjustments of the model

In chapter 4, it has been doubted whether pupils would be sufficiently challenged to continue with the process of modelling. Therefore, the scenario explicitly offered examples of further questions about known behaviour of liquids and solids, as well as known phenomena that were difficult to explain by means of the model and a few situations that asked for a prediction. The previous analysis showed that pupils indeed further applied and adjusted the model. An analysis of which specific interventions encouraged pupils to continue after their initial modifications follows below.

Question:

Which problems specifically challenged pupils to further apply and modify the model?

Outcome:

Following initial adjustments, one group was clearly not motivated to continue with the process of modelling. The most important questions and problems that did encourage them to make further adjustments, were those concerning different substances having different boiling and melting points (cf.fragments 2:8.2 and 2:8.4 above) and differences between crystals of different substances. A few other problems did not so much result in new assumptions, but did challenge pupils to consider the behaviour of the balls in more detail. These will be illustrated below. As was expected, differences between final models concerned further refinements, but the comparison at the conference did not result in further adjustments. Instead, conceptual problems became more apparent.

Illustration of the outcome:

Following initial adjustments, the new models were applied to several phenomena (cf. activity 20). As two pupils did not attend the subsequent lesson, only two groups continued their work at this stage. At first, one of these groups was not at all motivated to further apply their adjusted model.

(2:7.10) [T=teacher]

T: But how is your ehm, for we don't have much time left....

Ni: But I have, I already know everything.

T: You already know everything, that's quite smart, but I hope the others do too and that later on ehm, and that later on you'll be able to defend it.

Vs: But what's there to explain? It just all fits, the balls are also in liquids.

Ni: We're really great you know, we think of it at once.

(2:7.13)

T: Right, so now get going, for we don't have much time left ehm....

Iv: But we're already done, aren't we?

T: Well, I doubt that, for you still have to, there are still many other phenomena, see if you can explain those with your model. Look, when you can explain one phenomenon, you mustn't say that you're done.

Iv: We can explain everything.

Since they were very convinced that their model was correct, they did not see the point of applying it. They expected that they could do this, if they wanted, but that it would not bring up any new results. After being forced to continue nonetheless, they gradually became more and more involved. Specific problems in particular encouraged both groups to consider the behaviour of the balls in more detail. One such problem was explaining evaporation at room temperature: did the balls of water move so fast that they escaped the attractive force, or were they "kicked out" by the balls of air that collided against them at the top of the water? A similar problem was the prediction of the behaviour of water following removal of the surrounding air. Both groups initially thought that nothing would happen:

- the water would not expand because of the attractive forces between the balls;
- the water would not evaporate either for there would be no balls of air that could collide against balls of water.

One group tested their prediction. Just before this experiment was performed they were told that something would happen. They immediately began discussing this and with time the discussion became more and more guided by the model instead of macroscopic knowledge.

(2:8.8) [R=researcher]

Vs:	Because they get more space. They are not stopped, they go slightly further apart and then it becomes somewhat...., but then...., what's between those balls then?
R:	They are not stopped. Yes, what's between those balls then?
Vs:	So that's the question. Nothing.
R:	Nothing.
Vs:	That's normally too.
R:	Yes.
Vs:	Well then it does rise, I think.
(...)	
R:	*Ni* what did you think?
Ni:	Well I don't know exactly. I think it ehm, no I don't know.
R:	And *Jen* you thought it was going to evaporate?
Jen:	Yes, so, that the water is going down.
Vs:	But where do those particles stay then?
R:	Yes so it becomes less because some particles leave and those can....
Ni:	Yes that's what I think too.
Jen:	Maybe you get some condensation on the bell glass.
R:	Yes.
Vs:	(laughs) On the bell glass.
R:	And *Iv*?
Iv:	Yes it rises.

Jen and *Vs* attempted to find reasons to explain their prediction, and asked each other and themselves questions which further convinced them of their own opinion. *Ni* listened to most of their argumentation and tried to decide for himself. Only *Iv* did not really contribute. He had framed his prediction and simply wanted to perform the experiment which would reveal the answer.

The experiment was performed, i.e. a beaker filled with water was observed while the surrounding air was being removed. The outcome, namely the boiling of the water, came as a surprise and did not lead directly towards an explanation. The observation that the water had not become warmer although it had been boiling, was especially difficult to comprehend. In their initial explanations, they kept trying to find a mechanism to account for a higher speed of the balls. Finally *Vs* thought of an explanation.

(2:8.12) [R=researcher]

Ni:	Yes but then how can it be that such a ball is going to move faster?
R:	It wasn't going to move faster.
Vs:	It isn't going to move faster! It's going further apart.
Ni:	Yes but how, yes that's what I mean. But how does it work?
Vs:	Well because they're no longer stopped, because there's nothing to stop them so they can [go/be] further apart.

Iv: On the upper side, otherwise they were always kicked on the upper side by those balls of water.
Ni: But then it's not completely right what we say...
Vs: What?
Ni: ... for what is going apart? That distance between the balls thus becomes bigger?
Vs: Yes.
Jen: But so then it becomes a gas.
Ni: But then, yes so then it becomes a gas.
Vs: Well that's right isn't it?!
Jen: Then why does it have to behave so wildly?
Vs: Just look at that bell glass.
Jen: Yes but why does it have to behave so wildly?
Iv: Yes, that's indeed what it becomes, yes indeed, it did start to condensate, didn't it? Became a gas.
Jen: So in the end it'll all condensate?
Vs: And because the space between those balls is so big, those are the bubbles that you see, that move, those are the empty spaces. Do you understand it? Do you understand me?
Iv: Yes, no, you're right. We're right.

At this point they had to write their results on the poster. Therefore the conversation was finished before *Ni* and *Jen* could clearly show whether they understood the explanation. Nevertheless, their final remarks and questions indicate that they did understand the ideas of *Vs*. Moreover, they agreed to use these results as a major part of their presentation of the model, and they even framed a new problem, i.e. "why does it have to behave so wildly?". It seems that the latter was not yet solved satisfactorily.

In section 5.2.3 it has been shown that the two final models did not differ significantly. The main difference concerned the way in which the balls in liquids and gases moved. This became the major item during the subsequent class discussion and further illustrated the conceptual difficulties concerning perfect collisions. The second group started to question the first group's assumption of perfect collisions, which in their opinion could not coexist with the assumption of mutual attraction.

(2:9.3)
Ni: That's not possible at all.
Fr: And why not?
Ni: Because otherwise ehm, if you have such a ball, you have a whole bunch of balls that all bounce against each other and that all have mutual attraction. Why will they then always again, then, then it will always be the case that they come together, and then separate again but never as far. Then they will always separate a little bit less far from each other and then again come closer to each other.....
Wes: But as we have explained....
Ni: ....and again separate less far from each other and then again come closer together and eventually they will be against one another.
Wes: But are you now...
Al: No for they had such a perfect movement didn't they?
Ni: Yes, but if a mutual, if they have a mutual attractive force of course not for then that should mean that they, with one ehm, for example this is a ball, and this is, well, this ball bounces here, this ball bounces here, (inaudible), this is a ball, it bounces against this, this one has a mutual attractive force with this one, well this one bounces, and in your opinion the perfect, it must be very perfect, so that it gets such a speed, that it really gets a higher speed than it has when it goes against this. For when you have such a ball and it bounces against this and it goes ehm, ehm, and no speed is lost, then it would, then it never gets as far as where it just started.
Wes: But in which state do you consider the balls? In a solid, liquid or gas?
Ni: Doesn't matter. Just at a fixed temperature.
Wes: It does matter, because... (inaudible)

Ni: (inaudible)....ever less far will it get, because the mutual attraction...
Iv: Doesn't matter whether liquid, gas or solid. Doesn't matter in any way.
Wes: It does.
Iv: Well, explain what difference it makes then.
Wes: Well, we have just done so....
Al: *Bo* will explain it.
(....)
Bo: Yes you say, you only take two balls against each other into account, that bounce against each other, right? But meanwhile there are also other balls that attract this one ball. So you don't have, so does the attractive force only influence those balls?
Iv: Yes but, isn't it like, the closer together a ball is the stronger the attractive force? Those other balls are not immediately on top of them, for if they would all be on top that would mean that they're all on top of each other at once, and then ehm, you ehm, always have a solid.
Vs: But then they would really never collide if the attractive force from each side were just as big.

The answer of *Bo* was inadequate, as *Iv* and *Vs* showed, but their discussion was of a surprisingly high level. They were able to examine the influences of balls that were close together in combination with the effects of the forces of more remote balls. When *Bo* realised that his argument did not hold, he tried a new one.
(2:9.4) [T=teacher]
Bo: It's also like, those balls do not go, they do not stick together. They slam against it very hard and then the other balls shoot away from each other again.
Iv: But still, in the end....
Fr: It has to do with the speed.
Iv: Yes, but, look here...
Vs: But if you have attractive force, and you get for instance, you always lose speed. When you come together and you're attracted then it is harder to leave.
Fr: But because the speed is big with a gas, it can also get further away.
Iv: No that's rubbish. I think that's nonsense. No but...
T: Ehm, Mrs *Al* has a remark, I understand?
Al: Yes, with that elastic so and so, whatever it was, but that, wasn't that precisely that they didn't ehm lose any force during the bouncing?
Ni: But then they should faster ehm, by one bouncing they should then get more force.

It seems that *Bo* attempted to explain that even though sometimes two or more balls might be together for a while, they are likely be torn apart again because of collisions with other balls. *Fr* added that all this could be possible because of high speed, and finally, *Al* pointed out that the assumption of perfect collisions prescribed that no speed was lost. However, the second group did not agree with any of these arguments, for in their opinion the attractive force would always decelerate the balls after a collision, independent of the circumstances. Subsequently, the first group was not able to generate new arguments to support their model and therefore the second group was asked to explain how their model avoided this problem of deceleration and still assumed attractive forces. Following their explanation, the first group tried to criticise their assumptions.
(2:9.5)
Al: And you consider it as simple that they all turn around each other and what then happens...
Iv: No who's talking about simplicity?
Al: The principle of Ockham, you were supposed to keep it as simple as possible....
Vs: But if it's not right...
Ni: Well we could indeed not find a ehm better...
Al: No but what happens with gas?
Iv: No it is also quite simple I think. With gas? Well then they go much further apart.
Ni: Then they go off the curve.

(...)

Al: Oh right, and then when it goes from gas to liquid, then it first went off the curve and then it suddenly thinks "hey I'll go back in the curve".

Vs: No because they go slowly, then they go more slowly and then they come together and then they attract each other again.

The above fragment shows that the use of the principle of simplicity was not a convincing argument. It seems that simplicity was a matter of taste and not a criterion to choose between assumptions. During the class discussion, it became increasingly clear that although the first group had changed the model as little as possible, they were not able to resolve the conceptual difficulties of the other group. The latter not only had a reason to change the model more thoroughly, as was briefly reflected in "But if it's not right...", but also could defend their mechanism against other arguments, as was shown above. The first group, however, did not ask them how the balls could begin to move faster when the temperature was raised. Since the second group no longer seemed to assume mutual collisions, they should put forward a new mechanism to account for faster moving balls.
Instead, in the end, the first group could not do other than defend their assumption of perfect collisions as being something that just did not occur in daily life, just as the teacher had done previously (cf.section 5.5.3).

(2:9.6) [T=teacher]

Al: That is the perfect movement, isn't it, that it doesn't loose any speed? Yes I don't know either.

Vs: Well I never saw such a bouncing ball, that ehm...

Al: No, but you also can't see them.

(They laugh)

T: So that's their assumption. As I understand, so this group says, so they can, those bouncing balls that, ehm, those very tiny bouncing balls that you can't see they bounce so well we assume that they, yes....

Ni: I have an example...

(..... The example is about a well known toy)

Bo: What *Ni* just said, what *Ni* just said just isn't right.

Al: No in my opinion you can't compare this with something earthly, for that perfect movement is only there, that, doesn't occur in any other way with ehm things that normally occur in the daily world, in my opinion. Only with ehm, that's why, it was a bit hard to assume it, for I don't know it at all.

Iv: Well what a coincidence, that it just exactly by coincidence (inaudible)

Ni: Yes but, alright then. Let me just...

Al: Yes (inaudible)

T: But so that's an assumption, for something that you can't see but by means of which you can still explain the phenomena.

Ni: Yes but, boy, we find it bad, ours is much better.

Again, this line of defence, although supported by the teacher, was not convincing. The teacher subsequently suggested to try to combine the two models, however *Iv* put forward that they had also explained the outcomes of a specific experiment, namely the boiling below the usual boiling point, and he wanted to know whether the other group could explain that. From the above line of reasoning it is obvious that, in this case, it could not function as a decisive experiment: both models could be used to give the same explanation.

Discussion

The previous analysis showed that pupils did not pose many further questions themselves. They did however see the importance of specific problems, namely those that immediately

forced them to discuss adjustments to the model. The scenario did contain some of such problems, but a larger collection should be strived for.
Furthermore, it appears that our choice not to teach about mean velocities of particles or about the effect of the mass of particles on the course of collisions, did not have any negative consequences. These issues did not prevent pupils from making progress in their process of modelling. On the other hand, such issues could encourage pupils to think through the behaviour of the balls in even more detail, for instance when talking about evaporation below the boiling point or about differences in the behaviour of different substances. Conceptual problems concerning perfect collisions, however, did prevent pupils from making further progress. The previous examples of conversations clearly showed that these pupils lacked the necessary knowledge about the effects of forces. They should at least understand that, because of mutual attraction, the balls are not only slowed down when moving apart, but also accelerated when moving towards each other.

5.5 The nature of particle models

5.5.1 Introduction

During their involvement in the process of modelling, pupils should also learn about the nature of particle models. This learning should be initiated by experiences of applying and adjusting the model described above. Reflection on these experiences was intended to reveal the important aspects of the framework of particle explanations. In section 5.5.2 it is discussed to what extent the scenario succeeded in showing pupils these aspects. Furthermore, the hypothetical nature of the model was emphasised by a focus on the existence of the particles. In section 5.5.3 it is discussed to what extent pupils were encouraged to reflect on this existence.

5.5.2 Reflection on particle explanations

In this section it is investigated to what extent teacher and pupils were able to summarise explanations that were given, in such a way that the framework became more explicit. Subsequently, it is discussed whether, in retrospect, a content related motive for such an explicit reflection can be found. And finally, it is analysed to what extent pupils considered the particles of the model to be different from tiny bits.

Reflection on particle explanations that were given

It was attempted to make the framework of particle explanations explicit by means of pupils own results. To this end, firstly, summaries of specific explanations were presented in a special format, which at a later stage was also used to give a summary of all particle explanations. By then, it was expected that pupils would be able to express, in general terms, what they had been doing each time they gave an explanation.

Question:

How easily could teacher and pupils give a general summary of their previous explanations?

Outcome:
The teacher could easily summarise specific explanations, however in the beginning not all pupils comprehended the purpose of these summaries. Arriving at a summary of all explanations given thus far, was much more difficult. Pupils only talked about specific examples, i.e. what they did in that particular situation. This was partly encouraged by the teacher, but it also appears that pupils were not yet able to reflect on these examples from a more general perspective.

Illustration of the outcome:
Section 5.3.3 already illustrated that pupils' own explanations, given in activity 4, were sufficient to show the hypotheses that were implicitly framed. While summarising pupils' own explanations, the teacher only had to encourage pupils to describe the behaviour of the balls in some more detail. The latter should still be further improved in order to emphasise the importance of collisions. Furthermore, at the time, some pupils did not really understand the purpose of these summaries in one format.

(2:3.2) [T=teacher]

T: But I distinguish an attitude of, well, is this really worthwhile, that's kind of what I hear you saying....

Vs: Well, I do comprehend the model, but I do not really understand that it was very important for this sequence of lessons so to say.

T: No, and why did you think that....

Vs: Well sort of because we did not always come back to the model, but also kind of used the format and such. Yes, I don't know, I find it all a bit vague.

T: You find it vague.

Vs: Yes.

T: And you consider the format, the format vague?

Vs: I do understand each of it, but I don't get the logic of it, of it all.

At the end of activity 11, the teacher started a general reflection on all the explanations given.

(2:5.1) [T=teacher]

T: So, in short. Each time, we had an amount of gas, which had a pressure, a volume, and a temperature, and it had a mass, that was the initial situation, and then we would change something, yes, then we would change something and then we got a final situation. We would, for instance, compress, we would heat it, we would do all kinds of things, so that was what happened on the visual side, that's where we changed things, and ehm, yes what ehm, what happened ehm... and then we would, on this side we would explain it by means of the balls and ehm, what ehm, who would like to add to this, what ehm, how did it continue? What did we do then? .... So, sort of try, with this framework, sort of try to summarise all the phenomena that we examined to summarise that in one framework. On the left are the things that we, that we did ourselves, the compressing of the gas and so on, that's on this side, and then on this side we had the balls, and ehm who can...

Wes: [you mean] if you change the amount, change the space or something, the volume?

T: Yes.

Wes: Then what happens?

T: Then what happens, yes. Something changed, something happened, yes.

Wes: Well, if you change the volume, then ehm there are more balls on a smaller space.

T: Yes, more balls on a smaller space, then what did we, that was the reasoning on this side, yes.

Wes: By means of which the balls thus bounced more often against the wall, because of which the pressure became higher.

T: And then the pressure became higher yes. [are there] Any other phenomena that we had [discussed], that we can incorporate in this framework? We just talked about compressing a gas, what other things did we do that fit into this framework?

Other pupils that were asked to add to this conversation either did not know what to say (*An*, *Jen*) or also put forward a specific phenomenon (*Vs*). The latter was discussed quite extensively. As a result, the teacher had barely any time left to discuss the invariance of the balls. He simply asked whether the balls remained the same when during a change at the macroscopic level and several pupils agreed. Then he quickly argued that they had explained changes by means of things that did not change, and he stated that this occurred more often in daily life. He reasoned that people did different things all the time while meanwhile staying the same person.
During the final interviews, pupils were asked to describe in general terms what they did when they gave particle explanations. They were explicitly asked not to give specific examples, but to talk about all the explanations together. None of the answers agreed with what was expected (cf. section 4.4.6). Only one answer shared aspects with the expected description.

(Int.Ni/Bo) [R = researcher]

Ni: You first translate everything into balls, molecules or whatever. Well, and then ehm, with all that you know, with all those properties of those balls, you're going to try to search for a solution.

R: Yes, and how do you do that?

Ni: Well then you first have to know what's going on. Well and then you're going to examine how that can be. (Bo laughs) And then what really happens, and then you're going to examine how that can be. And then you have to take the first situation into account. And then you can explain the second situation.

Besides *Ni*, none of the other pupils mentioned a translation, although one (*Wes*) did mention rules that they had learnt. In addition, most of them did not talk about an initial and final situation. They only said that they simply thought about, or imagined, what happened to the balls. For instance:

(int.Jen/We)

Je: Then you first examine what exactly happens at a certain experiment. And then you just try to imagine where the balls are and what happens next. Well and then you'll manage somehow.

These outcomes show that, although pupils were increasingly capable of giving explanations in line with the framework, they could not yet discuss the framework itself, i.e. they could not describe first comparing the initial characteristics of the gas to a specific initial state of the moving particles, subsequently considering what would happen to these balls and finally translating the final state of the collection back to the macroscopic level. Pupils may well need more practice in using the model, and the two kinds of hypotheses most likely need to be more explicitly distinguished during previous reflections, before pupils are able to clearly define what it takes to give such explanations.

A content specific motive to reflect on previous explanations

In the discussion of section 5.4.2, it was already argued that the comparison between hypotheses for the connection between the temperature of a gas and the model should not be finished until complete frameworks within which explanations were given (cf. figures 5.6-9) can be compared. Such a comparison of frameworks could then in turn prepare for a subsequent reflection on the general framework of particle explanations.
We suggest that a first reflection on explanations should not be forced on pupils by means of summaries in activity 5, but should take place at the end of activity 8, when frameworks such as those of fig.5.4 and 5.5 are explicitly compared. If necessary, this comparison

can even involve a third framework, for instance when pupils decide that it may still be possible to connect the temperature of a gas to the diameter of the balls. Especially the emphasis on the difference between T⇔v and T⇔t, should give the teacher the opportunity to focus pupils attention on the nature of previously (implicitly) established connections between macroscopic properties and the model. Subsequently, pupils can choose one of the frameworks in order to explain their solution to the problem of how the balls can come to move faster. This procedure may help pupils find a solution, because it would give them a better idea of the way in which they understand the problem. In addition, it will make the differences between suggested solutions of activity 9 more clear. Since these differences concern hypotheses about the behaviour of the balls, these hypotheses can then explicitly be distinguished from earlier ones, which concerned connections between the model and macroscopic variables.
After the mechanism of transfer of momentum is selected as the most favourable compared to other solutions, the teacher can once more emphasise the difference between T⇔v and T⇔v,t by showing fig.5.6 and 5.8. This will automatically focus pupils attention on the question whether the balls themselves do or do not become warmer. Then it will become plausible to assume that the balls themselves do not change and pupils may even be able to understand that it is exactly the invariance of the balls that makes the model so powerful.

The invariance of the particles

During the second trial, the process of teaching and learning did not yet take the above course, due to already discussed shortcomings of the scenario. Nevertheless, the framework for particle explanations did guide pupils' subsequent modelling, as already appeared from section 5.2.3 and 5.4.4. Important, in this respect, is that pupils appreciated that the balls differed from tiny bits of matter.

Question:

In what sense did pupils understand the idea of invariance and did they consider this assumption plausible?

Outcome:

All pupils considered the invariance of the balls to be a sensible principle. Most of them argued that otherwise one needed to explain how the balls themselves could change. For some pupils, this invariance implicitly did not refer to the temperature of the balls (e.g. *Fr*, *Iv*). In addition, most pupils indicated that in explanations they had indeed mainly considered the movements and positions of the particles, and not, for example, their shape.

Illustration of the outcome:

A first rough indication of pupils' ideas about the nature of the particles is their list of basic assumptions. After discussing the existence of the particles, the teacher asked them what they already knew about the particles. During this inventory, the following list appeared on the blackboard:

they have speed (can change)
fixed mass and diameter
are very small
they move

(2:5.10) [T=teacher]
T: Anything else? Anything else that was mentioned? Or is that about it? Yes?
Vs: That's about it.
T: That's about it, yes. Right, so that's what we know. Ehm, let's see. And ehm yes we, do those balls change themselves? Those balls that we talked about. Do those balls change?
(Some pupils say "no")
Wes: (inaudible)
T: *Wes*, you say they change because of the heat?
Wes: They don't change in magnitude or something, but they change in speed.

So all basic assumptions were gathered, except the hypothesis of collisions, which is quite essential in order to explain pressure phenomena. Change of speed was mentioned, however, and most pupils did mention (perfect) collisions during the final interviews. Moreover, all pupils expressed the opinion that the balls themselves did not change, but only their speed. Two pupils (*Va*, *An*) could not give a general reason for the invariancy and instead repeated why the balls did not become heavier. All others explained that if the balls changed themselves then an explanation would need to be derived for how this change happened, or that they did not need to assume such a change because they could explain everything by means of the movement of the balls. Although they were not able to precisely describe what explaining by means of a particle model consisted in, many pupils did indicate that they mainly considered the positions and movements of the balls. For example:
(int. Iv)
Iv: ...but in any case you consider, you consider the movement of the balls. And when they move such and such, you consider the effect, for instance the water around it or the gas around it, [the effect] that it has, well doesn't it have any effect or maybe it does have an effect on the other substance, and then ehm you consider the movement and you consider what this movement brings about and then you can probably explain it.

It was expected that, as pupils knew little about the balls, they would agree not to add any new assumptions to the list unless they really could not do without them. This suggestion did not even have to be put forward by the teacher, for one of the pupils already pointed out that the model should be as simple as possible.
(2:5.11) [T=teacher]
T: No, until now we didn't need any changes in the balls. And that's something that in science too, that's also something that we should consider....
Vs: It should be as simple as possible.
T: *Vs*, as simple as possible, how did you think of that?
Ni: (inaudible) difficult.
Vs: Yes.
Ni: Then you never get an ehm...
Vs: I mean, an explanation is the best if it is as probable as possible, as simple as possible.
T: As simple as possible. We do indeed, that's magnificent *Vs* what you're saying, we always take an explanation that is as simple as possible. And until now we didn't need the balls to change, so then we don't assume that either.

The transcript shows that the teacher could easily build on the answers of *Vs*. He only needed to add that they had indeed kept the model as simple as possible, for instance by assuming that the balls do not change. In addition, the teacher was meant to give a further example of this guideline by asking them whether the balls needed to be spherical. This did not happen until the next lesson. Some pupils had already talked about this question during their group work, while they were discussing whether the balls existed.

(2:5.5.b) [T=teacher]

Ni:	I said that the theory of balls could be right. It could also, instead of those balls, it could also be something else.
T:	Oh, right.
Vs:	Squares or something.
Ni:	Triangles.
T:	Oh, yes, right, but....
Vs:	No, no, not triangles.
Ni:	Yes indeed, triangles too.
Vs:	Pyramids, for triangles...
Ni:	Yes, alright, or blocks, cubes.
Vs:	That could be, trape...
T:	Why not triangles? *Vs*?
Ni:	Well, that's not three-dimensional.

These pupils understood that the exact shape of the balls was not an issue. They did not need to make specific assumptions about the shape, besides that they were three-dimensional, because their shape was irrelevant in the explanations. This conclusion was not clearly drawn in the next lesson. Instead, these pupils mentioned that although the particles could also be cubes, this was less likely, for the edges would probably wear off. The teacher subsequently further emphasised that they already assumed that the balls did not change (so if they were cubes they would stay cubes), instead of explaining that it was, as yet, unnecessary to make any assumptions about the shape at all.

5.5.3 Reflection on the existence of the particles

In the first version of the scenario, the existence of particles was not emphasised, which in turn resulted in several unwanted consequences. These results are illustrated below and it is discussed how these results were taken into account in modifications of the scenario. A content specific motive for pupils to think about the existence of the particles was then expected to be raised by means of reflection on the value of the model developed so far. In the remaining part of this section it is discussed whether this motive emerged and whether subsequent activities were considered to be adequate to fulfill it. In addition, it is investigated whether pupils' belief in the existence of the particles increased and, moreover, whether they could explain why they had become more convinced.

Results of the first trial

At the end of the first trial, in their final written reflection on the sequence as a whole, several pupils showed that, in their view, the model of balls was only an imagination and that these balls should not be considered as realistic. The following examples serve as an illustration.

Ma (FR1)
I can now imagine, for example, why air wants to spread across the space, but I don't find it logical, because those balls seem so unrealistic.

To (FR1)
I did learn a lot, but what I find difficult is that you easily tend to suppose that, in reality, air is also randomly moving balls.

Na (FR1)
If you assume that the theory of balls is indeed correct and it is really like that, then I can say that I learnt a lot. (..) I don't know to what extent it is possible, but if more experiments could be done that support the theory of balls, it would become more credible.

Je (FR1)
(...) it's only a model, for you still don't know whether air really are balls (...) I started to think about air differently, although you do not know for sure whether it really is like that, I do now consider air like that, I'm not sure whether that is convenient.

Besides some minor difficulties, this point of view caused two conceptual problems. Firstly, one of these pupils thought that since the particles did not exist, they could not design experiments to investigate whether the model was adequate. In other words, he could not conceive the strong relations between macroscopic observations and the model.

(1:3.2) [T=teacher]

T: Other ideas? Could we think of an experiment in which you could, for we said last time it is a ridiculous idea those colliding balls, could you now think of an experiment with which you would say that you could really see it move, that sheet of paper if that really shook, if that really were those coll..., it should shake a bit, could you now think of an experiment by means of which you could perhaps... Why did you say, why did you just say...

Ma: But it is only a model, isn't it?

T: It's only a model, yes, no, but...

Ma: So then you can't see either, if it is not like that, then you neither can think of an experiment by means of which you can see that.

Secondly, another pupil thought that they could change the model in any way they wanted, as long as it was still adequate for explanations. It seems that she did recognise the relations between the model and macroscopic observations, but at the same time barely perceived restrictions in development of the model.

(1:5.3) [T=teacher]

Fl: But you can just "cut and glue" whatever you, in the model, whatever you want, can't you?

T: As long as it ....

Fl: As long as, yes,...

T: ...can...

Fl: ...as long as you can explain it.

T: As long as it agrees with what happens in reality, yes. Yes.

Fl: But I mean, the speed of those balls, you can't, basically you can't know that either....

T: No.

Fl: ...so you can't really know whether they turn left or right.

The positive aspect of these results is that these pupils were not convinced that matter really consists of tiny balls. Furthermore, none of the other pupils showed that they were indeed completely convinced of this. In that respect the approach succeeded in teaching the hypothetical nature of the model. This was mainly due to not telling the pupils what matter consists of, avoiding the term "molecules", and involving them in the development of the model. On the other hand, pupils in the above examples stayed too close to the idea that matter is unlikely to consist of particles or that it is impossible to derive the structure of matter anyway. In addition, this attitude made some of them doubt the relevance of the knowledge which they developed.

Several reasons for the above results can be indicated. The previous fragments of conversations show that the teacher made a clear distinction between, on the one hand, the ("ridiculous") ideas about the balls and, on the other hand, what happens in reality, as if the particles were not at all realistic.

(1:2.2) [T=teacher]

T: (...) when we make such crazy assumptions (...) then we call that a model.

(1:5.1)

T: (...) and then there was nothing left than to say that in the model, the speed, the speed of the balls in the model is the temperature in reality.

Although Brownian motion was also observed in the first trial, it happened much sooner and was not explicitly used to reflect on the existence of the particles. Pupils were able to predict what would happen as a result of collisions against an object, i.e. it would shake a little, but testing this prediction was not connected to a possible change in the degree of confidence in the model. Instead, pupils were asked to design an experiment which would allow them to see these vibrations, but this assignment proved to be too difficult. The whole scenario contained only one moment of explicit reflection on the reality of the assumptions.

(1:5.5) [T=teacher]

T: Is it really like that, the speed, or is that, is that something that we only imagine? Well, how could find out about this? Whether the balls really, whether the balls are real? Whether this kind of balls really have a speed? What should you, in what way should you, should you act? Do you really think it is like this or ehm, do you think it is an idea?

Br: (inaudible) if you can see it.

T: You think it is only real, that it is certain, that you can see it, yes.

Br: I think so.

T: And how would you eventually, how would you eventually become a little more certain whether the balls, well maybe they do exist after all, maybe not, how would you...?

Br: If you have very many things that you can indeed explain. (inaudible) logical (inaudible).

T: So like we did until now?

Br: Mmm. [confirmation]

From this fragment we learnt that in order to encourage pupils to form a balanced opinion about the existence of particles, they should establish that they cannot see these particles through ordinary microscopes, and they should explicitly consider what other kinds of experiences could positively influence the degree of confidence in their existence.

Existence of the balls: second trial

In the second version of the scenario, reflection on the existence of the particles was started by means of a discussion about the value of the model developed so far.

Question:

Did the question whether the balls exist become important and did pupils consider the subsequent activities adequate in order to answer this question?

Outcome:

The question was not raised in the intended way, because the teacher did not act according to the scenario. The question had, however, already been posed before, and the class discussion did bring forward different opinions concerning the issue. Some pupils thought that the model was only an aid to come to a better understanding, in the sense that they were better able to imagine how gases behave. There were also pupils who suspected, from the beginning, that the balls were molecules or atoms. As this was not confirmed, even these pupils were not completely sure about the existence of the particles. Some pupils argued that, if the balls did not exist, they had not explained anything at all. The subsequent activities were considered sufficiently adequate to investigate whether the balls existed.

Illustration of the outcome:
From pupils' written reports and fragments of their conversations several opinions concerning the existence of the balls emerged. Some pupils initially thought the balls were not real.

Al (HW2:4)
And even if it aren't really balls, which I do not really believe, I was at least more able to imagine it by means of this.

Jen (HW2:4)
In my opinion the balls are invented, I at least have never seen them with my own eyes.

(2:4.1) [T=teacher]

T: (...) but ehm, so if they become bigger, then you have to, then you should eventually be able to see that through a microscope, shouldn't you?
Fr: Those balls are imaginary, aren't they?
T: Are the balls imaginary?
Fr: Yes, aren't they?
Wi: Or not.

Some pupils did not yet mention ideas concerning the existence, or explicitly adopted a neutral position.

Bo (HW2:4)
The balls could really exist, but I don't have real indications for that, but no indications that it could not be either.

Furthermore, some pupils suspected from the moment that the model was introduced, that the balls were probably atoms or molecules, whereas at least one other pupil at first believed there was no connection. Just before the discussion concerning the existence of the particles, she began to question whether these balls weren't molecules or atoms after all.

Ni (HW2:2)
I find the model of balls very clear and very easy. I think that in the end a link will be established between the balls and molecules.

(2:1.8)

Wes: Yes but liquid, that is that the balls are close together but not move so much, isn't it? They pass each other....
Fr: It has nothing to do with molecules. It has nothing to do with molecules.
Wes: Oh right, that's with molecules.

Fr(HW2:4)
By means of the model everything could be explained so far. It is clear. Only I would like to know whether the balls really exist, are they atoms or not?

Others realised that if the balls did not exist, then they had not explained anything at all.

Wi (HW2:4)
Maybe they really exist, the experiments of which we derived them are also real, and if they do not exist, the theory of balls is not right either.

(2:5.4) [T=teacher]

Wi: Look, if ehm, we have, we assumed the balls because ehm, in order to come to a better understanding, but if the balls do not exist then the theory isn't right either.
T: Yes, yes, well what do we think of that? Anyone else who wants to say something about that?
Wes: I think that we haven't proved yet that those balls exist. That we at least use them as an aid in order to explain it logically.
T: I see. So now we still use them as an aid.
Wes: Yes, and maybe, if later on we're going to examine how it works exactly, that we will see that it, that they exist after all.

(Somewhat later in the same conversation)

Wes: I think, because we assumed all the time that there are balls in there and it consists of balls and by means of that we can explain this and that, but if they do not exist, then we just used something

	while it is not like that at all.
T:	No, but which was useful to us in order to explain things.
?:	Yes.
T:	But maybe yes...
Wes:	But then you, if they don't exist, you never find out the cause.

These different opinions were not sufficiently explained and defended by pupils during the class discussion. The teacher should have started the discussion by encouraging pupils to reflect on the value of the model. It would then probably have become clear that some pupils considered it a useful aid to imagine how gases behaved or why they behaved in such a way. It could subsequently have been discussed whether all pupils found this sufficient to consider the model relevant, and in their argumentation the question whether the balls exist could have become important. For, as some pupils said: if the balls did not exist, the theory would not be right either.
As several pupils had already asked whether the balls were visible or imaginary, the teacher decided not to discuss the value of the model, but to ask whether the balls did exist or were indeed imaginary. Instead of encouraging a discussion between pupils who offered different points of view, the teacher tended to defend the idea that the model was, so far, just an aid to understand the behaviour of gases. He did not encourage them to talk about possible experiences that could change their minds concerning the existence of the balls, but only mentioned that they would try to find more indications for this existence and that the worksheet and the microscopes would help them do this.

Since possible influences on pupils' opinions were not discussed, the pupils were not sufficiently introduced into activity 13. They were not made fully aware of their own ideas concerning experiences that may change their minds, and therefore could not yet conceive how the next activity was expected to help them answer the question concerning the existence of the particles. In other words, their motive to start the next activity remained rather vague. Although the pupils did not precisely know what they were going to do next, most pupils seemed to find it worthwhile to find out whether the balls could be seen through a microscope, for this question was already raised and had not yet been answered. Some pupils seemed to be a little disappointed that the particles could not be seen. At that point it was not clear to them that the rest of the worksheet would still help them to answer the question about the existence of particles. Some even had to be encouraged by the teacher to continue with the group work.

In order for pupils to make a prediction concerning the behaviour of the parts of smoke, they needed to imagine two things. Firstly, they needed to imagine how the smoke parts would behave, i.e. what they would see through the microscope, if there was no air, or at least if there was no effect of moving balls of air. And, secondly, they needed to imagine in what way the parts of smoke would behave differently because of their interaction with the moving balls of air. Two of the three groups developed a prediction quite quickly. Of one of these groups, the process of arriving at this prediction was recorded. This process clearly showed the two conditions:

- one pupil immediately explained that the pieces of smoke would move in all directions because they were pushed by the balls of air that collided against them [i.e. behaviour because of interaction with moving balls];

- another pupil offered the possibility that the pieces of smoke might not move at all because the balls of air might be to small (i.e. "normal" behaviour if there was no effect of balls of air).

The third group did not easily make a prediction. The following transcript illustrates that they did not yet imagine what they would see through the microscope if there was no effect of moving balls, nor how the parts of smoke would behave differently because of their interaction with balls of air. At first, they only considered what would happen at a macroscopic level. *Al* had already written down that maybe those pieces of ash "smoked off" hot air, "but they weren't bigger either". When they were asked whether they already had made a prediction they said not to have done so. They were then asked to imagine what they would see through the microscope.

(2:5.7) [R=researcher]

R: If you imagine air as a collection of balls and you add such a piece of ash, then what would happen to that piece of ash?[R=researcher]
Al: It would be cooled.
R: Why?
Al: Because the air is colder.
R: Yes, and what is, what is cooling, when you describe that by means of the balls?
Al: They become slower.
R: Yes.
Va: They're going to mix.
R: They're going to mix, so you have, so to say, a few pieces of ash, and around it you have all these moving balls of air.
Al: They become slower and visible or something. No, for you don't see normal air either.
R: You don't see normal air, but you can see those pieces of ash.
Al: Yes but those aren't air, are they?

At this point they still had no idea what they would see through the microscope when examining smoke, with or without the influence of invisible moving balls of air. After persuading them again to imagine visible pieces of smoke amidst invisible moving balls of air, *Al* suddenly imagined what she would see.

(2:5.7) [R=researcher]

R: No, but what, if you, what would happen with those pieces of ash, which you can see, and which are in this little room with all these moving balls of air.
Al: Oh, you see it move. That piece of ash, for they bounce against it all the time and then you see it move.
An: Those balls?
Al: No that piece of ash. (Inaudible)
Va: That piece of ash moves, because it is pushed by the balls.

Reflection on increased belief in the existence of the balls

All pupils therefore saw that their prediction was right. This observation was expected to increase their belief in the existence of the particles.

Question:

Did pupils' belief in the existence of the particles increase and to what extent could they explain the reasons for this increase?

Outcome:

Most pupils did become more confident about the existence of the particles and they could sufficiently explain how this had happened.

Illustration of the outcome:
The groups that rapidly developed a prediction, both considered the outcomes of the experiment as an indication that air could consist of balls. At least two pupils of the third group still had their doubts. None of the pupils could think of an alternative explanation of their observations. The worksheet encouraged them to discuss why they thought these experiences were a new indication and how important they considered this result. The extent to which this activity influenced their opinion differed, which was illustrated in the reports and conversations of this lesson. Some pupils thought that the indication was quite convincing.

Fr (HW2:5)
So after this experiment you can assume that air consist of balls.
Bo (HW2:5)
This could almost only be caused by the balls. So this is a strong indication that the balls really exist.
Wes (HW2:5)
Because of this we had to change our conclusion. The balls do exist. (...) At first I thought that the balls were made up in order to explain everything / more phenomena. Now, after the last experiment, I think that they do indeed exist.

(2:5.5b)

Jen:	And how important do you consider, well quite so ehm....
Vs:	How important do you consider this...
Jen:	For....
Vs:	Quite important, isn't it?
Jen:	Isn't it?
Vs:	I find it quite important.
Jen:	Mmm (affirmative). For it means that there is something in the air.
Vs:	Yes there is something that makes the ash, those things, move.

Other pupils were slightly more cautious.

Ni (HW2:5)
Is this enough proof that the balls exist. Of course not, but it was indeed a good start.
Al (HW2:5)
Because of this we concluded that, in principle, it could be that they exist. But our group agreed that, if they existed, we would already have heard about it. But we have heard about molecules. It could of course be that they are the same.

All pupils could be grouped in one of these two categories, i.e. "quite convincing" and "slightly more cautious", except *Iv*, who did not participate in the above group work, and *Wi*, who hardly participated in these discussions and did not hand in the homework of this lesson.

Another activity that was explicitly incorporated in the scenario in order to increase pupils' belief in the existence of particles, namely arriving at the same speed of the particles in two different ways, was less effective in this respect. First of all, pupils were barely motivated to find out how fast the particles moved. When the teacher asked for remaining questions in activity 15, this particular question was not put forward until the teacher persuaded pupils to think of more questions. Secondly, pupils did not agree that the two results were more or less the same. Therefore it was not possible for the teacher to stress that the agreement may increase their belief in the existence of the particles. Thirdly, the transfer of results to pupils who had not made the calculations themselves was quite poor. Although explicitly asked, not all pupils mentioned the results of other groups and hardly any pupils explained how these results were reached.

There was, however, another important influence on pupils' degree of belief in the existence of the particles, for more and more pupils gradually began to suspect that the particles might be molecules or atoms. It appeared that this was closely connected to the question about the existence of the particles: the more their knowledge about the balls agreed with their knowledge about molecules the more they seemed to believe that the balls did exist. Although some pupils had already learnt that the existence of molecules was not certain either.

(2:5.4) [before the examination of smoke] [T=teacher]

Fr: Well, maybe it would truly exist.
T: Maybe it would truly exist.
Fr: That they are atoms, or something, or is that impossible?

(2:5.9) [after the examination of smoke] [T=teacher]

Va: I don't think that they exist.
T: You don't think that they exist. And why don't you think that?
Va: Then I would have known before. Then it would be known. In chemistry or something.
(Several pupils talk at the same time. The teacher asks *Va* to continue.)
Va: Yes, exactly, it could be, but it is a bit strange, for if it truly consisted of balls I would have known sooner, I mean I've also had a few years of chemistry and also with air and stuff, but I never heard anything of balls.
(Somewhat later in the same conversation)
Wi: But look, for in chemistry we have, then we had, then we had that vanderwaals ehm force, we also saw ehm, when something is solid, a solid, that ehm, then the balls were almost all against each other, and with ehm, with a liquid they move slowly towards each other, they moved around each other and with a gas they were very far apart. But....
T: You saw that in chemistry?
Wi: But when you cool a gas, then those, then those balls are going to move slower, so maybe they also move towards each other and then it becomes liquid.
T: Yes. But did you really see those balls?
Vs: No, but that's a theory. And that agrees exactly with this.
Wi: So that is indeed logical.
T: But *Va* says I never heard of it. How can that be?
(Pupils talk at the same time.)
Vs: That's just called differently.
T: That's just called differently. What is it called then?
Vs: That are just all molecules.
T: So in your opinion, what we're discussing, those balls, they're the molecules of chemistry?
Vs: Yes, I think so. For that all agrees well. Like with the gas and stuff, yes.
T: *Va*, what do you think. Could it be those molecules?
Va: It could.
T: It could be, yes.
Vs: But molecules aren't certain either.

The teacher's reaction in this transcript appears very adequate. In the start of the sequence, it was still quite effective to ask pupils to only consider balls and no other particles that they may have heard of before, because at this time it was far from certain that these balls were indeed molecules. However eventually pupils saw many similarities and therefore the teacher had to give pupils the opportunity to explain what they already knew about other particles. In addition, he did not tell pupils whether their suspicions were right or wrong, for that would have meant that there were definite right and wrong answers, and thus no uncertainty. Instead, he attempted to make pupils realise that what they already knew about molecules was mostly knowledge which they had heard but not found out themselves. The latter was confirmed in the interview with the two highest ability pupils.

(Int Ni/Bo) [R=researcher]

Ni: I couldn't explain anything with those molecules, but concerning those molecules I already knew that it was right, and ours was not completely right yet, because we didn't know all of it yet, we were still investigating. So.

R: And how did you know that all that concerning molecules was right?

Ni: Well, that's written in every textbook, chemistry book and all.

Bo: That's what you just learn. (..) Then you may assume that it's right.

During the interviews at the end of the sequence, pupils were asked whether all along they had thought that these balls of the model truly existed. They were also asked whether their opinion had changed during the sequence and which experiences had caused this change. Almost all pupils stated that they were more convinced that matter consists of particles. Eight pupils mentioned that, at the introduction of the model, they were either unsure about the existence of the balls or had not given it much thought at all. Only three pupils, *Wi*, *Ni* and *Iv*, said that they believed that the balls were molecules from the start of the sequence and therefore already thought that they existed. *Ni* said he became (even) more confident during the sequence, the other two did not change their opinion. All other pupils indicated that they became more certain about the existence of particles.
Three causes for this change of opinion were indicated. Five pupils pointed at the behaviour of smoke particles as an important reason for them to become more confident. Two of these pupils, namely *Fr* and *Al*, also mentioned that with time, the balls more and more agreed with molecules or atoms. The other four pupils who changed their minds indicated that they were able to explain more and more phenomena. Eight pupils added to this that they would become even more convinced if they could see the balls and one pupil would be more certain if he could explain phenomena of which they had not thought yet. Being able to explain everything and working with the model for a long time were also indicated as reasons for becoming more convinced. Although examination of the behaviour of smoke particles was mentioned by more than half of the pupils who changed their minds, none of the pupils explained in general terms that being able to frame a correct prediction could or did further increase their belief in the existence. Furthermore, arriving at the same magnitude of the speed of balls of air in two different ways was not put forward at all.

5.6 Summary

In this chapter, the course of the actual process of teaching and learning has been compared to the expectations presented in chapter 4. We now briefly describe the main results and refer to chapter 6 for further discussion.

- We did not sufficiently succeed in preparing pupils for the introduction of the model in the intended way. It seems preferable and possible to provide pupils with a stronger motive for the introduction of the model. The way in which such a motive may be raised is discussed in section 6.4.3.
- The intended theoretical orientation towards a more general application of the model emerged to a reasonable extent. The final models, however, did not completely fit into the framework of particle explanations. An improvement of the knowledge that pupils have previously developed at a macroscopic level, and more emphasis on the correspondence between the speed of the particles and the temperature in the final part

of the approach, seem to be necessary (cf. sections 6.4.2 and 6.4.3).

- Pupils seemed to accept the model as a useful means to explain phenomena of air pressure. However, in subsequent explanations the role of collisions was not emphasised. In order to improve this situation, previous activities should be designed in such a way that searching for mechanistic explanations becomes a more important aim for pupils. The way in which this aim may become worthwhile is discussed in section 6.4.3.
- At some instances, the actual process of modelling differed from our expectations. In order to encourage pupils to establish the intended correspondence between the speed of the particles and the temperature, complete explanatory frameworks should be explicitly compared. During this comparison, it should become clear that the mechanism of transfer of momentum indeed serves as an adequate way to account for $v_{low} \rightarrow v_{high}$ whereas a truly plausible mechanism to account for $t \rightarrow v$ cannot be found. All pupils accepted the hypothesis of empty space between the particles, but several pupils only initially accepted the assumption of perfect collisions. At a later stage, the latter assumption led to important conceptual difficulties, which were not adequately solved.
- Concerning the nature of particle models, it was found that reflection on particle explanations can be improved (cf. section 6.4.3). Reflection on the existence of the particles more or less proceeded according to the scenario.

6 Evaluation and reflection

6.1 Introduction

In the previous chapter, the process of teaching and learning was described and analysed. This subsequent chapter deals with evaluation of the approach. Firstly, in section 6.2, pupils' opinions on the approach are summarised and discussed. Secondly, the teacher's view on the approach is summarised and, based upon his opinion and the results of the previous chapter, it is discussed which special requirements a teacher needs to comply with, in order to be able to teach according to a problem posing approach (section 6.3). In section 6.4, the analysis of chapter 5 and the opinions of pupils and teacher are used to answer the research questions presented in the first chapter. In reflection on these answers, a structure for the introduction of a particle model in secondary physics education is presented. Finally, in section 6.5, the approach is reflected upon to make some suggestions concerning teaching and learning physics in general.

6.2 Pupils' evaluation

At the end of the process of teaching and learning, pupils were asked to give their opinion about the sequence as a whole. Following the first period of testing, pupils were only asked to answer a questionnaire (cf.appendix C), and following the second trial, pupils were also asked to express their opinion during the final part of the interviews (cf.appendix D). In the following sections, results of both investigations are discussed.

6.2.1 Questionnaire

The questionnaire was designed prior to the first trial in order to obtain a general impression of which parts of the sequence pupils did (not) enjoy and whether they found what they learnt was worthwhile. This information was useful for revision of the scenario. After the second trial, the same questionnaire was used to compare the results to those of the first trial. In this section, pupils' answers of the first trial are summarised. Subsequently, some differences between the answers of the first and second trial are discussed.

First trial

Following the first trial, the questionnaire was completed by twelve pupils. Many of the pupils indicated that they had learnt to explain phenomena by means of a model. Some, however, explicitly mentioned that they already knew most of what had been taught, or that they did not know what they had learnt. Furthermore, several pupils explicitly mentioned that they had not learnt much. It seems that these results are strongly connected to the following:

- a perceived emphasis on knowledge that had previously been developed, instead of on

new knowledge concerning particles;
- a too weak connection between the model and "reality", resulting in some pupils believing that the model was only an imagination and should not be considered realistic (cf. section 5.5.3).

These two aspects are supported by answers to questions concerning what pupils did (not) enjoy. Some pupils, for instance, complained that there had been too much repetition of what they already knew or that the lessons often had proceeded too slowly. In addition, some indicated that they had enjoyed asking and answering questions, but complained that the answers were not always satisfying. It therefore seems understandable that the model was not fully accepted and that some pupils suggested to incorporate more experiments that could support the model.

Pupils' other answers to questions concerning what they did (not) enjoy were quite diverse. It seems that several pupils appreciated to have been involved in the process of modelling and that they had enjoyed the discussing and reasoning, especially in small groups. However, several pupils complained that too many questions concerning the behaviour of gases had been raised and that class discussions had taken too much time. Finally, as compared to other physics lessons, six pupils clearly stated that they had less appreciated this sequence, whereas five pupils considered this sequence better.

The above results were taken into account during the revision of the approach. In particular, it was attempted to more clearly emphasise the existence of the particles, to less emphasise knowledge that had previously been developed, to more clearly structure the problems that pupils raise concerning the behaviour of gases, and to make the whole approach more problem posing.

Second trial

Following the second trial, the questionnaire was completed by eight pupils. Because of the small numbers, no conclusions can be drawn concerning differences between pupils' evaluation of the first and second scenario. Nevertheless, the comparison of results contains some interesting aspects.

After the second trial, a larger fraction of the pupils mentioned that they had learnt a lot. This result corresponds to other answers concerning what pupils did (not) enjoy. These answers indicate that there was less repetition during the second trial and that the model was considered more relevant. An increased belief in the existence of the particles seems to have contributed to the latter.

Furthermore, the second collection of answers displays a less negative evaluation of the sequence as a whole. Again, about half the pupils seem to have liked the approach more than the average lessons. This time, the others either did not give a clear answer (besides their references to the video camera), or did not notice real differences. Whereas half the pupils of the first test clearly stated that they did not enjoy the sequence as much as most other physics lessons.

Pupils' remarks concerning positive aspects of the approach seem to mainly refer to their own active involvement (discussing, thinking for themselves, framing questions, etc.). Concerning negative aspects, again, class discussions were considered to have taken too much time. In addition, some pupils complained that at some points they had not been allowed to proceed in a direction that they preferred, which indicates that the sequence was not considered sufficiently problem posing. Pupils' own active involvement and their appreciation of the problem posing character of the approach are further discussed in the next section.

6.2.2 Interviews

Following the second trial, interviews were conducted with all eleven pupils (five pairs and one single). The final part of these interviews consisted of questions concerning the way in which pupils had been working during the sequence. The outcomes were analysed from two perspectives, relating to the constructivist idea, and to the problem posing idea respectively (cf. section 3.2):

> *To what extent did pupils themselves believe that they were more actively involved than in other lessons, and did they appreciate this kind of involvement?*
>
> *To what extent did they understand why they were involved in specific activities, and did they enjoy working from specific questions that were raised?*

The answers to these questions will indicate whether the approach was experienced as being problem posing and, if so, whether pupils enjoyed being involved in such a process of teaching and learning.

Active involvement

In response to the open question concerning the way in which they had worked during the sequence, six pupils in five separate interviews stated that they often had to think for themselves. Four of these pupils spontaneously added that, because of this, they had come to a better understanding or were better able to remember what they had learnt. In two interviews this was spontaneously confirmed by the other pupil. One pupil mentioned that she had found this thinking quite difficult. Another pupil was disappointed that the teacher hardly confirmed any of their results.

In comparison with other lessons, also chemistry, nine pupils stated that in this sequence concerning a particle model, they had to think much more than usual, whereas in other lessons the theory was explained and they simply had to make several exercises. Although not explicitly asked, many of them indicated that this sequence about a particle model had brought them to a better understanding, and/or that other lessons were less enjoying. Only two pupils did not notice real differences. Compared to the questionnaire, these results can be understood as mainly referring to differences with chemistry lessons. In these lessons, pupils appear to be told that matter is made up of atoms, having specific properties, which knowledge they subsequently have to apply in some situations. Or, as one pupil said:

(int.Iv)

Iv: Well, chemistry is not a, I think, you don't ehm, is no science subject, really. It is necessary, for physics or so, but it is not really a subject that requires thinking in three dimensions. It's just more like a language. So therefore it is, it is also just more, it is taught more like a language. So just learning. (...) I also don't really like chemistry, but...

The purpose of activities / working from specific questions

In response to the open question what pupils thought of the way in which they had worked during the sequence, three pupils almost immediately complained that at some points they had not been allowed to proceed in a direction that they preferred. A fourth pupil made a similar remark at the end of the interview, when specifically asked about his opinion on working from induced questions. All of them were high ability pupils. Three of these

were the same pupils who also stated this disadvantage in the questionnaire. Their examples of such instances, in which they were pushed too much in one direction, concerned three different kinds of situations:
- having to consider a suggestion by the teacher which they would not have suggested themselves; more specifically, having to judge the effect of warmer balls on the force that these exerted by means of collisions;
- questions that the teacher did not want to explore; more specifically, how the balls of a flame had come to move faster and how heat could be connected to the model;
- having to continue with one solution, whereas they themselves had thought of a different one; more specifically, having to use the idea that balls can move faster because of collisions with other faster moving balls, while there was no opportunity to explain a different solution, namely in terms of energy.

These instances all refer to their coming to see the point of assuming that, when a gas is heated, the balls come to move faster without becoming warmer.
When explicitly asked whether there were any activities of which they did not understand the purpose at the time, six pupils mentioned that they did not understand the initial activities. Five of these were high ability pupils. Two of them did not understand the part concerning regularities. Two others did not understand the relation between the announcement that the next lessons would deal with the behaviour of matter, and the initial activities, that mainly dealt only with air and the model. Two low ability pupils explicitly mentioned that they could only remember activities of which they understood the purpose. Moreover, they considered this to be very unusual, for in other lessons they often did not understand why they had to perform a specific activity.
In addition, there were a few remarks about two particular activities that were, although understood, considered unnecessary, uninteresting, or not worthwhile, by particular pupils, namely the calculations of the speed of the particles and the final debate. The latter, however, was also specifically mentioned by just as many pupils as being a good or enjoyed activity.
None of the pupils explicitly showed spontaneously that they enjoyed the problem posing character of the sequence. All pupils who were asked whether they had recognised that the process was structured around main questions, confirmed that they had and stated that they liked this approach. Four pupils made an additional remark. Two of these remarks concerned the fact that they were not allowed to differ from the main path; the third pupil stated that she would not enjoy asking "why" all year; and the fourth one stated that it sometimes took a long time before they found a solution, however it was nice when they did, for it made her feel wise.

Conclusions

The previous results are indications of the way in which the pupils appreciated the problem posing nature of the approach. In comparison to more traditional lessons pupils felt more actively involved in the development of the model. In addition, apart from a few specific activities, they felt they had understood what they were doing and why. Their examples of instances that were not problem posing agree with the analysis of chapter 5, i.e. the initial activities before the model was introduced, the forced evaluation of the hypothesis "temperature of the balls", and not being allowed to present and use a specific solution. And, finally, it appears that they had mostly enjoyed participating in the approach, as far as it was indeed problem posing.

6.3 The teacher's role

Following each lesson, the process of teaching and learning was evaluated by the teacher. Several parts of these conversations were used in the analysis presented in chapter 5. In this section, information from these discussions is analysed in order to answer the following questions:

Which aspects of the approach did the teacher find difficult to handle and what did he learn during the course of the research?

Which requirements does a teacher need to comply with in order to be able to teach a problem posing approach?

These questions will be answered in sections 6.3.1 and 6.3.2 respectively. The contents of these sections have been read and confirmed by the teacher.

6.3.1 The teacher's evaluation

The main difficulties indicated by the teacher concerned teaching according to the scenario. Even though, or maybe because, he participated in development of the approach, it was not easy for him to distinguish between details and main ideas. In the beginning, he found it difficult to prepare the lessons, which improved considerably during the first trial. In the second trial, he experienced that the better he understood the main line of the scenario, the less it felt like a straitjacket. The management of class discussions then became the most difficult part to handle.
These conclusions will be examined in more detail below. First, we will consider the difficulties and results of the first trial, and subsequently the evaluation of the second one, in which also the teacher's overall attitude towards the approach is summarised.

The first trial

In the first period, the teacher experienced five kinds of difficulties. Three of these concerned teaching according to the scenario, namely preparing the lessons, keeping the course of the lessons in line with the scenario, and dealing with unexpected questions of pupils. The other two difficulties arose from the fact that the scenario did not adequately build on the knowledge that pupils had previously developed. The teacher's difficulties will be further discussed below.
In order to prepare for the lessons, he read the latest version of the scenario and attempted, as well as he could, to memorise what he had to do at which moment and what he could expect from pupils. After several lessons had passed, it was concluded that this way of preparing was not adequate, mostly because during the lessons he was not sufficiently able to focus on the main line of the intended process of teaching and learning. Being involved in development of the approach clearly had not been a sufficient preparation for teaching, and it probably even caused him to read less actively during the final stage of his preparation, for most parts he had already seen before. These difficulties were, at least partially, solved when the teacher, instead of memorising every detail, started to make an abstract of subsequent lessons of the scenario. In this way, he was more actively involved, and forced to separate the important steps from details for himself.

As a result, it was also easier to keep the remaining lessons in line with the scenario. Still, he found it quite difficult to respond to pupils' suggestions. In his own lessons he would often improvise in order to follow up on an interesting remark, for instance by showing an extra experiment or by further investigating a particular line of thought. He thought that the scenario prevented him from doing this. Also, he did not know how to deal with unexpected questions, especially when these concerned issues that were already dealt with. Whereas he would usually reopen the discussion, he now felt that he had to continue in order to finish the scenario in time.
A further difficulty relates to the fact that the activities of the first version of the scenario did not yet sufficiently respond to pupils' own questions. That is, the intended questions were not experienced as interesting problems and it was not clear enough for pupils how subsequent activities would help them to find answers. This resulted in a less positive atmosphere and in the pupils becoming more passive, which in turn made it quite difficult for the teacher to continue. Finally, it became apparent that the pupils did not have all the required macroscopic prior knowledge that the scenario presupposed, which not only delayed the whole process of teaching and learning but also confronted the teacher with some poor aspects of earlier teaching.

The second trial

During the second period, the teacher believed he was under a greater pressure, because he felt responsible for the success, or failure, of the research. Besides dealing with this extra stress, he still found it difficult to teach according to the scenario and, in particular, to manage the class discussions.
Based upon the experiences with the first trial, this time the teacher made an abstract of each lesson of the scenario, which was discussed before the lesson took place, in order to check whether the main line was understood. During previous lessons, he had also ensured that pupils had obtained all the required knowledge about macroscopic behaviour of gases. In addition, the scenario itself was improved. Therefore, it was often easier than in the first trial to keep the course of the lessons in line with the scenario. Nevertheless, he still found it difficult to handle those moments at which the process tended to differ too much. For instance, when pupils' responses did not clearly fit into the plan, or when activities took more time. At those instances, as well as at the beginning (when it was not sufficiently clear to pupils what they were doing and for what reason), the scenario still felt like a straitjacket.
Such instances mainly occurred during class discussions. In these activities, it was difficult for him to ensure that:

- a review of the previous lesson would not take too much time;
- discussions about various hypotheses would stay transparant for all pupils, and would lead to a decision within the available time;
- discussions would show progression in the intended direction, in such a way that pupils would consider it worthwhile;
- all pupils would pay attention to the results of other groups, which was easier when they did not agree with each other;
- he understood the arguments of individual pupils, while he was also dealing with the organisational aspects of the activity.

During the second trial, the teacher learnt that the better he was capable of staying on the main path, the more he felt comfortable in teaching according to the scenario. This was further improved when he could find some quiet time, in order to concentrate on his abstract, just prior to the lesson.

While reflecting on the second scenario as a whole, the teacher's overall attitude towards the approach was quite positive. He had enjoyed teaching the sequence and he had obtained the impression that pupils had also liked the lessons. He believed that the approach was well-designed with much variety. He was impressed by the extent to which the pupils had been motivated to participate in the activities, in spite of several negative influences such as the time of year (just before the summer holidays), the beautiful weather, and the distraction created by the video camera. He considered the scenario to be a considerable improvement compared to his own previously developed sequence about particles, and intended to use the approach again in future years.

6.3.2 Demands

After combining those elements of the analysis of chapter 5 that concerned the teacher's role, and the difficulties that he himself experienced, we arrive at a collection of requirements that a teacher needs to comply with in order to teach a problem posing approach to an introductory particle model.

Firstly, the teacher needs to be convinced that pupils are sufficiently capable of reasoning, at their own level, about experiences and pieces of knowledge that they encounter, in such a way that it results in "something good". Secondly, the teacher needs to be able to establish and maintain an atmosphere in which all individuals listen to others. More specifically, he needs to ensure that:

- all pupils pay attention, especially during class discussions;
- all pupils have sufficient opportunities to bring forward their own ideas, especially when these differ from what is already discussed;
- pupils' expressions are interpreted adequately and not judged too quickly, which is quite difficult, not in the least because it can take some time to find out what a pupil really means.

Thirdly, the teacher needs to be able to keep the process of teaching and learning in agreement with the main line of the approach. That means that he needs to:

- deal with differing and usually unexpected remarks and questions of pupils, for instance by explaining why specific questions cannot yet be dealt with, or by sometimes allowing the process to differ a little;
- make pupils' own answers part of the general outcomes as much as possible, for instance by using their own expressions in summaries of the outcomes;
- ensure that all pupils see the main line of reasoning, for instance by asking them to give a summary, or by emphasizing how a next activity builds on a previous one.

The latter is quite important. Such an emphasis can, for instance, involve a focus on the results of the previous activity and an explanation of how the next one promises to lead to an answer to the raised question. It can and should even involve allowing pupils to proceed according to their own plan when possible and productive within the main line. Finally, the teacher needs to be able to recognise the main issues in class discussions and emphasise these as such.

6.4 Evaluation in light of the main research questions

6.4.1 Introduction

In this section, the analysis of the actual process of teaching and learning (cf. chapter 5) as well as the opinions of pupils and teacher are used in order to answer the research questions presented in the first chapter.

1. *To what extent did we succeed in designing a process of teaching and learning during which pupils reach the intended aims?*

In section 6.4.2, this question is answered by means of an evaluation of pupils' achievements on the two kinds of intended aims, namely those concerning the specific particle model and those concerning the nature of particle models.

2. *To what extent does the course of this process of teaching and learning empirically support the adequacy of the choices that were made?*

In section 6.4.3, this question is answered by means of an evaluation of the main content specific choices, as well as the basic ideas, that were discussed in chapter 3. This evaluation further contains suggestions for improvement of the approach. In section 6.4.4, the answers to the above questions are reflected upon, in order to show the main characteristics of the approach and how these are connected. As a result of this reflection, a structure for the introduction of a particle model in secondary physics education is presented.

6.4.2 Evaluation of the results

In chapter 5, it was discussed to what extent the process of teaching and learning took place in the way it was intended. Subsequently, in this section, it is discussed what has been achieved by pupils who participated in this process. The evaluation only concerns those pupils who attended all nine lessons (*Al*, *Wi*, *Wes*, *Fr*, *Bo*, *Fr*, *Jen*, *Vs*, *Ni*). Thus, references to "all pupils" only concern these eight pupils.

Achievements of pupils

As a result of their participation in our approach, pupils were expected to develop and apply a model similar to the first six items of the list of De Vos and Verdonk (1996), and to learn about the hypothetical nature of particle models. Concerning the specific particle model, their achievements on each item are discussed.

1. All matter consists of entities called particles. Individual particles are too small to be seen. They behave as hard, solid, and (except in chemical reactions) immutable objects. Their absolute dimensions and shape are usually irrelevant. In drawings the particles may be portrayed as small circles or dots.

This aim has been reached quite well. Many of the pupils seemed to understand that, apart from dimensions and shape, other assumptions about the particles, such as their temperature, can also be considered as irrelevant, because all macroscopic change is explained in terms of movement (cf. sections 5.4.2 and 5.5.2). Some pupils assumed that the size of the particles can be relevant in order to explain differences between different substances, for they argued that bigger particles exert a larger mutual attraction (cf. sections 5.2.3 and 5.4.4).

2. Motion is a permanent feature of all particles, because of the perfect elasticity of collisions. There is a direct relation between the temperature of an amount of matter and the average kinetic energy of its particles.

This aim has been reached to a reasonable extent. All pupils seemed to assume that the particles of solids move (cf. section 5.2.3) and to have established a correspondence between the temperature of an amount of matter and the speed of its particles (cf. section 5.4.2; kinetic energy was not yet included). Furthermore, several other connections between macroscopic variables and the model were explicitly established in class discussions (cf. section 5.5.2). In addition, all pupils assumed that the ongoing motion of the particles is possible because the space between these particles is considered to be empty (cf. section 5.4.3), but only a few also assumed perfect elasticity of collisions in this respect. Others were not able to maintain the latter assumption because of conceptual difficulties that arose from the combination of perfect collisions and mutual attraction (cf. section 5.4.4). Pupils' final models still showed a too strong connection between the three states of matter and the relative speed of the particles. It is unclear whether this is caused by a strong connection between the three states and the temperature, which is likely to have been developed previously at the macroscopic level, or by a too weak correspondence between the temperature of an amount of matter and the speed of the particles (cf. section 5.2.3).

3. In a gas the empty space between the particles is much larger than that occupied by the particles themselves. Particles of a gas in an enclosed space are evenly distributed, implying that gravity has a negligible effect on them.

The hypothesis of empty space between the particles was accepted by all pupils (cf. section 5.4.3) as well as the assumption that the mutual distances are large between particles of a gas (cf. section 5.2.3). These distances have not been compared to the space occupied by the particles themselves. Implicitly, it was assumed that the particles of a gas in an enclosed space are evenly distributed, but this has not been connected to gravity.

4. There is mutual attraction between any two particles, but its magnitude decreases rapidly with distance. In a gas the attraction is negligible, except at high pressure and at low temperature, when it may cause a gas to condense into a liquid or a solid.

This aim has been reached quite well. All pupils assumed a mutual attraction between the particles, the effect of which decreases when the mutual distance increases, so that it is negligibly small in a gas (cf. section 5.2.3). Although not explicitly dealt with as such, it also seemed to be clear to many of the pupils that, in the case of a large concentration of particles (i.e. at high pressure) or a low speed (i.e. at low temperature), the influence of the mutual attraction is bigger, as a result of which a change of state can occur (cf. section 5.2.3).

5. In liquids and solids the particles are much closer together and subject to mutual attraction. In solids the particles are arranged in regular patterns, with each particle being able only to vibrate around a fixed position. In liquids the particles are irregularly arranged and move from place to place.

This aim has been reached to a reasonable extent. The assumptions concerning differences in movement of particles of solids, as compared to those of liquids, were established, as well as hypotheses concerning differences in mutual distances and attraction as compared to those of gases. However, there was no emphasis on regular patterns and a too strong connection between the three states of matter and the speed of the particles. In addition, the assumed mutual distances between the particles of liquids were too large as compared to those of solids and gases. The latter may have been caused by a lack of macroscopic knowledge concerning the relative volumes of a fixed amount of matter in the gaseous, liquid and solid state (cf. section 5.2.3).

6. Different substances consist of different particles, but all particles of one substance are mutually identical. A mixture contains particles of two or more different species.

Differences between particles of different substances were assumed, sometimes even quite specifically, i.e. differences in size, mass and mutual attraction (cf. sections 5.2.3 and 5.4.4). Implicitly it was also assumed that all particles of one substance are the same. There was no emphasis on mixtures.

> (...) the particulate nature of matter is associated mainly with the following phenomena: solids, liquids, and gases and phase transitions; diffusion and dissolution processes; heat and heat transfer (..). (De Vos & Verdonk, 1996, p.659)

The actual process of teaching and learning, described in the previous chapter, suggests that all pupils eventually learnt to give sufficient explanations for phenomena of gas pressure and conduction of heat. This result was checked by means of two questions during the interviews. One of these dealt with the pressure of air in a football and the other with pressure differences of the air in two connected syringes (cf. appendix D). Most explanations were adequate, because pressure differences were correctly accounted for in terms of changes in the frequency and/or impact of collisions and changes in speed were described as caused by collisions with other particles having a different speed. However, some remarks need to be made. Firstly, some of these explanations initially seemed insufficient or even incorrect, but upon further questioning, pupils were well able to improve their explanations. A similar observation has already been made in section 5.3.3. Secondly, in the complicated situation of cooling one of the connected syringes, some pupils did not fully take into account the double effect of a lower speed of the balls on the total force that is exerted by means of their collisions. Finally, pupils' account of how fast moving balls come to move slower as a result of collisions with slow moving balls remained rather vague, or even resulted in further conceptual problems concerning the combination of perfect collisions on the one hand, and the slowing down on the other hand. Based upon what has been taught in the approach, however, pupils could not be expected to give a better account or to resolve these difficulties.
The analysis of the actual process of teaching and learning also suggests that pupils' explanations for phenomena of solids and liquids, as well as changes of state, may be less adequate than intended. As far as explanations for such phenomena were given during the interviews, these support the analysis of sections 5.2.3 and 5.4.4. However, it appears that we have not obtained enough information, both from the process and from the interviews, in order to draw more detailed conclusions concerning pupils' performances in this respect.

Besides arriving at a specific particle model, pupils were also expected to learn about the nature of particle models. These aims were less specified. During the interviews, all pupils were able to describe the purpose for which they had been using the model. They either mentioned explaining phenomena (more easily), understanding (more) phenomena, being able to (better) imagine the course of phenomena, or to solve problems (more easily). Many of them indicated that, in using the model, they mainly considered the positions and movements of the balls, and that the balls themselves did not change (cf. section 5.5.2). During the process of teaching and learning, all pupils were actively involved in framing and evaluating hypotheses, and during the interviews they were all able to explain why specific hypotheses had or had not been incorporated in the model (cf. sections 5.4.2 and 5.5.2). In these responses pupils clearly separated these hypotheses from observations used to evaluate them. In addition, during the interviews, all but one suspected that a further development was necessary, although only a few were able to give some indications of reasons why and ways in which. The interviews also indicated that many of the pupils had learnt that, upon further modelling, they should keep the model as simple as possible and mostly maintain the assumptions that were already incorporated (also cf. section 5.5.2). During the process almost all pupils became more convinced of the existence of particles and could describe results that had influenced their degree of belief in this existence. These descriptions, however, mostly referred to the observation of specific events, in particular Brownian motion. They barely reflected on these events in more general terms: only some pupils mentioned that they became more convinced because they were able to explain more phenomena, none mentioned the influence of testing a prediction (cf. section 5.5.3). Similarly, they were quite able to describe what they were doing when they were giving a specific particle explanation, but they did not seem to be able to give such a description in more general terms, i.e. referring to two kinds of hypotheses, and how these are used in an explanation (cf. section 5.5.2).

Modification of the aims

The actual achievements of the pupils give reason to believe that, within an improved approach, pupils can indeed arrive at a model similar to the first six items of the list of De Vos and Verdonk (1996). Thus, this aim does not have to be modified. What such an improved approach should consist of is discussed in the next section. Concerning the nature of particle models, our approach provided pupils with many relevant experiences and encouraged them to reflect on these. However, these activities hardly resulted in general knowledge about the nature of particle models or, even more general, of physics. We now come to the conclusion that such a general aim is probably too far to reach within just one sequence, dealing with just one particle model.

Comparison to other results

In section 2.3, it has already been argued why we expect that, in many respects, the various innovative approaches that were analysed show only slightly better results than common teaching strategies. Compared to the results of these more traditional approaches, that have been discussed in section 2.2, it seems that pupils who attended all the lessons of our approach made use of particles that less resemble tiny bits.

Compared to the results of usual teaching strategies, pupils in our approach also seemed to have learnt more about the nature of the model, although not yet about models, or even physics, in general. The achievements concerning the nature of the model, that are described above, can more or less be classified as what Driver et al. (1996) and Leach (1996) have called "model-based reasoning" (cf. section 2.2). Compared to the framework of Carey et al. (1989), pupils seem to have reached an intermediate level 2/3. For instance, they did seem to understand that the goal of their modelling process was to better understand natural phenomena (level 2). In the approach, the model was developed in a cyclic cumulative way in order to arrive at a deeper explanation of known behaviour of matter, but most likely,

pupils did not yet consider this process as a specific example of "the cyclic, cumulative nature of science" which aims at "the construction of ever-deeper explanations of the natural world" (level 3).
Compared to the framework of Grosslight et al. (1991), pupils likely also reached an intermediate level 2/3. They did "take an active role in constructing the model, evaluating which of several designs could be used to serve the model's purpose" (i.e. their own purpose), and they experienced that a model "can be manipulated and subjected to tests" in "a cyclic constructive process" (level 3). However, the model was developed in order to come to a better understanding of known behaviour of matter, not "in the service of developing and testing ideas". So the main focus was "on the model and the reality modelled, not the ideas portrayed per se", and tests of the model were not "thought of as tests of underlying ideas but of the workability of the model itself" (level 2).

In summary, it is concluded that we succeeded reasonably well in designing a process of teaching and learning during which pupils reach the intended aims. Compared to the results presented in chapter 2, pupils in our approach seemed to have developed a model of which the particles are less similar to tiny bits and a more appropriate, although not yet very explicit view of the nature of particle models. Nevertheless, further improvement of the approach is necessary.

6.4.3 Evaluation of the choices and suggestions for improvement

The achievements described in the previous section are the result of the actual process of teaching and learning. In this section, it is discussed to what extent the course of this process and its results support the choices that were made when designing the approach. One such choice, namely concerning the aims that pupils were supposed to reach, has already been evaluated in the previous section. The other content specific choices are discussed below, including suggestions for improvement. Subsequently, it is evaluated to what extent the "basic ideas" presented in the third chapter are adequate for the topic of particle models.

A theoretical orientation

The approach aimed to induce a theoretical orientation towards known behaviour of gases and, at a later stage, of liquids and solids. Although the intended initial orientation was not sufficiently raised, it seems that, at a macroscopic level, pupils' knowledge about relevant phenomena of gases was adequate. However, concerning all three states of matter, macroscopically, more attention should be paid to the co-existence of two states at the same temperature. At a later stage, pupils may then come to realise more explicitly that, at one specific temperature, the speed of the particles of one substance in two different states has to be the same. Furthermore, in order to prevent incorrect assumptions concerning the relative mutual distances of particles, pupils should already have learnt that, under the same circumstances, a fixed amount of matter has approximately the same volume in the solid and liquid state, which is very small compared to the gaseous state. Finally, perfect collisions need to have been dealt with before the start of the approach, in such a way that conceptual difficulties mentioned above no longer occur. Consequently, it will perhaps also be possible to make the correspondence between the temperature of an amount of matter and the model more precise: instead of to the speed of the particles, the temperature can then be connected to their kinetic energy.

In the second version of the scenario, apart from the announcement that they were going to deal with behaviour of matter, the first activity did not really give an impression of what they could expect during the next nine lessons. It was expected that the latter would become clear as soon as the initial theoretical orientation was raised, which was intended to happen before the end of the first lesson. This theoretical orientation was not sufficiently raised, but even if it was, it would still have been better to start with a general introduction. This introduction may, for instance, consist of an historical account. Just as at the end of the approach, the teacher can refer to famous scientists in history, in order to show that people have always thought about the origin of everything around them, have tried to classify matter and have tried to figure out how it all works and what it consists of. In other words: philosophers and scientists have always searched for deeper explanations of what they encountered in the world, and nowadays they still do. In this way, the teacher shows in general terms what is going to be the issue of the next lessons and meanwhile builds on a possibly existing curiosity of some of the pupils. Presenting such a general impression may, however, raise an educational problem. Since, from the beginning, pupils' attention is much more focused on the structure of matter, the subsequent process of learning may be more influenced by factual knowledge about molecules or atoms. It cannot yet be estimated whether this influence will have negative consequences. Nevertheless, it seems preferable to at least not include words such as "molecules" or "atoms" in this first impression.
Following such a general impression, the intended theoretical orientation is to be raised. In this respect, the second version of the scenario only aimed to show pupils in what sense it could be worthwhile to come to a better understanding of already established generalisations, and which kind of generalisations they could not yet further explain. Apart from the fact that the scenario was not sufficiently adequate to reach these aims (cf.section 5.2.4), the approach would, we think, be considerably better if a more specific motive for the introduction of the model is raised. In order to induce such a motive, pupils' attention needs to be focused, from the start, on the structure of matter and, more specifically, on giving explanations in terms of the behaviour of constituting elements, which differs from the behaviour of the system as a whole. To this end, at an earlier stage, pupils should have become familiar with the differences between properties of a system and its constituting elements, and the way in which the different behaviour of these elements can explain the behaviour of the system. Examples of activities that can contribute to understanding the latter can be found in the examination of the working of the human body or man-made machines. The approach of Buck (1987) also fits into this scheme. In addition, pupils should somehow come to appreciate why some general statements (e.g., copper conducts electricity) are considered to be "law-like" whereas others (e.g., all coins in his pocket are made of copper) are not. The difference can intuitively be accounted for by the suspicion that the first can be further explained (i.e., that there is something about the nature of copper that explains why it conducts electricity), whereas the latter describe accidental coincidences. Finding out "why specific gas laws are as they are" can then be further specified as an investigation into the nature of a gas, in terms of which a deeper explanation can be given of its typical behaviour.
Combination of the above two ingredients may motivate a search for a deeper explanation of gas laws in terms of the behaviour of elements, which differs from the behaviour of the system as a whole. The question "why the gas behaves in that specific way" then much more refers to "how it works" and it becomes much more obvious to investigate what a gas really is in order to answer the question. In such a way, a model that contains particles

which differ from tiny bits can be more or less anticipated by pupils. We still should not expect that pupils themselves can put forward a model that is sufficiently adequate to start with and we thus still need to introduce one. But the model that is introduced would then fit into their general expectations and the specific behaviour that accounts for the macroscopic phenomena can be much more emphasised. In such an outline, again, the above educational problem of interfering factual knowledge about molecules or atoms may occur. Furthermore, it still needs thorough thinking to design the specific activities in such a way that pupils will indeed not only find it interesting to search for an answer to the question "how it works", but also come to find it worthwhile to think about the structure of matter and to search for an explanation in terms of the behaviour of constituting elements.

The theoretical orientation towards a more general applicability of the model was better raised. It therefore seems that extensive focus on the explanation of heat transfer as well as the emphasis on the general framework of particle explanations adequately prepare pupils for further modelling. However, since pupils' final models showed a too strong connection between the three states of matter and the relative speed of particles, it may be better to pay even more attention to the consequences of the assumed correspondence between this speed and the temperature.

Assuming that the above suggestions for improvements can be put into practice, it still seems preferable to initially induce a theoretical orientation towards known behaviour of gases, for reasons that were already discussed in chapter 3. The context of gases makes the introduction of moving particles plausible, and by applying and developing this initial model, pupils in our approach indeed arrived at the assumption of invariant particles. Furthermore, since the model is to be used to come to a better understanding of behaviour of matter, a theoretical orientation seems more adequate than a practical one. As a result, it is suggested not to introduce particles too early in the curriculum. Instead of the usual introduction at the age of 13-14, or even earlier, we recommend to postpone this topic as much as possible. In the Netherlands, this means until the end of the third grade (age 15), since it is obligatory to deal with this topic before the fourth grade. In earlier years of the curriculum, it seems much more appropriate to use pupils' intuitive knowledge about macroscopic particles instead of dealing with molecules. Not to change these ideas about macroscopic particles, but to describe or explain phenomena that do not need a more sophisticated particle model. For instance:

- longitudinal waves can be described as the subsequent compression of macroscopic parts of the medium;
- on the assumption that iron consists of tiny bits of iron that each have their own magnetic orientation, it is possible to think of the magnetising and demagnetising of an iron object in terms of order and disorder of the macroscopic particles;
- processes of filtration can be thought of in terms of macroscopic particles that are too large to pass through the holes of the filter.

Such an approach may prepare pupils in two ways for future learning about classical particle models. Firstly, the activities encourage pupils to describe and explain phenomena in terms of smaller parts. Secondly, it may be possible, at a later stage, to show that it was worthwhile to divide matter into macroscopic particles in these instances, whereas there are other instances that call for another kind of particles.

The introduction of the model

The model of moving and colliding balls was sufficiently simple and could be applied immediately. Pupils were often able to imagine well the behaviour of a collection of balls in specific situations, most likely on the basis of their knowledge about the behaviour of macroscopic balls. Although previously learnt knowledge about molecules was raised, this did not influence the process of teaching and learning in a negative way.
The computer simulation did seem to make the model intelligible. In addition, it appears that such a way of presenting the model can postpone questions, concerning the ongoing movement of the balls, which indeed are better raised at a later stage. The expected benefits of the analogy could not really be tested. All pupils seemed to initially accept the model and many initially believed that the balls did not exist, but whether these results are a consequence of the way in which the model was presented cannot be deduced.

Modelling

During the approach, pupils were actively involved in the process of modelling, in the sense that they themselves framed and evaluated hypotheses. These hypotheses concerned the correspondence between the collection of particles and the macroscopic system, the behaviour of the particles (e.g., empty space, perfect collisions), and the adjustment of the model so that it can be applied to phenomena of gases, liquids and solids.
It was chosen to extensively deal with the correspondence between the temperature of the gas and the speed of the particles, as it was expected to make the invariance of the particles plausible and to contribute to a theoretical orientation towards a more general applicability. Although the approach requires further improvement, it seems that the emphasis on this correspondence is indeed important. From the actual process of teaching and learning we have discovered that this correspondence cannot be properly established unless pupils also prefer an explanation of heat conduction in terms of transfer of momentum above other suggested explanations (and especially ones in which the particles themselves become warmer or colder). Therefore, they should not be forced to establish this hypothesis at an earlier stage.
Initially, many pupils may implicitly connect the temperature of the gas to the temperature of the particles, which in the end is unwanted. This implicit connection may be strengthened by the analogy, which asks pupils to compare the behaviour of a gas to the behaviour of macroscopic objects, i.e. balls, instead of to the behaviour of particles of a still hypothetical nature but with not all the properties that macroscopic objects have. However, exactly because several pupils make this connection, a motive emerges to reflect on the correspondence between macroscopic variables and model variables, and even on complete explanatory frameworks. In other words, even if the analogy initially strengthens the unwanted connection, in the end this can be used productively and more explicitly in order to promote conceptual development. It will then be possible to explicitly compare several suggested frameworks as a result of which the process of decision-making can become more clear (also cf. section 5.4.2).

Before hypotheses concerning the behaviour of the particles of gas are made, the framework, and in particular invariance of the particles, should first be emphasised. It was found that addition of the assumption of empty space was far less problematic than is supposed in the educational research literature. It therefore seems appropriate to arrive at this hypothesis in the process of accounting for the possibility of ongoing motion. Furthermore, it was found that pupils, at least, do need to have developed some knowledge about the behaviour of perfectly elastic objects in the presence of forces, in order to be able to accept the hypothesis of perfect collisions. The alternative option, not to include this hypothesis at all, will not prevent conceptual difficulties at a later stage, when the model is adjusted in order to account for known behaviour of liquids and solids. Especially ongoing motion of the particles of solids will then be very difficult to maintain.

Because the theoretical orientation towards a more general applicability was strong enough, pupils initially needed less guidance in order to adjust the model than was offered. Subsequent activities were, however, still necessary in order to sustain the process of modelling. These activities need to make pupils wonder whether their adjusted models are already fully adequate. Furthermore, additional emphasis on the correspondence between the temperature and the speed of the particles may still be necessary at this stage.

The nature of particle models

During the development of the model, pupils were expected to also learn about the nature of particle models. In particular, it was attempted to involve them in a reflection on the nature of particle explanations (e.g., invariance of the particles, framework of explanations) and on the existence of the particles.

In an improved approach to development of the correspondence between temperature of a gas and speed of its particles, the establishment of this correspondence should, as just outlined, be accompanied by a choice for an explanation of heat conduction in terms of transfer of momentum. The preference of the resulting explanatory framework over one in which the particles themselves become warmer or colder, in itself asks for an explicit comparison of both frameworks and for an explicit reflection on the nature of the particles, which in turn make the assumption of invariant particles plausible. During this reflection, the difference between these invariant particles and the balls of the initial model should be discussed.

The course of the actual process of teaching and learning indicates that pupils, at the age of 15-16, are able to reflect on the existence of the particles well. This reflection seemed to contribute to their appreciation of the nature of the model, especially because their belief in the existence of the particles was influenced by their own experiences and not by authority of the teacher.

In the second version of the scenario, reflection on the process of modelling consisted in a summary, which was given by the teacher. A motive for such a reflection has not yet been found. Finding such a motive appears to be (even) more difficult than finding reasons for reflection on the contents of the model or, for instance, on the nature of the particles. Nevertheless, we still believe that such a reflection is important, especially to show pupils that scientists nowadays arrive at their knowledge about the structure of matter in similar (but much more complicated) ways.

Basic ideas

Our approach builds on what pupils already know or intuitively understand. We make use of their knowledge concerning macroscopic phenomena, the behaviour of moving and colliding macroscopic objects, and of their intuitions about regularities and analogies. These are not used to induce conflicts, but to raise and fulfill motives for the introduction, application and development of a model. The results of this approach indicate that both

the educational constructivist idea, and the idea that the knowledge which pupils have previously developed is largely correct, are adequate for designing teaching strategies that deal with the topic of particles. In our approach it has not been necessary to initially elicit and subsequently devaluate pupils' own ideas. Instead, specific expected difficulties, such as the implicit connection between the temperature of the particles and the temperature of the macroscopic amount of gas, or the acceptance of empty space between the particles, were dealt with at appropriate stages during the process of conceptual development.
Taking suggestions for improvement into account, the problem posing idea seems useful for designing teaching strategies that deal with particles. It still appears possible to induce an appropriate theoretical orientation and, to a reasonable extent, we seem to have been able to raise the intended local problems. Nevertheless, in order to further support the teacher, some general guidelines will have to be given as to how to deal with unexpected solutions of pupils, as well as to those of their questions that differ greatly from the main line (cf. section 6.3). Furthermore, several activities need to be improved, so that pupils are better able to understand how such an activity will help them to solve a specific problem. If such improvements are also taken into account, pupils seem to appreciate a problem posing approach (cf. section 6.2). Moreover, the problem posing character of our approach seems to have contributed substantially to the better results in comparison to common teaching strategies, because pupils developed the model on grounds that they themselves could understand.
Recent research of Maskill and Pedrosa de Jesus (1997 a) indicates that in common strategies, many pupils most likely do not understand why specific assumptions of taught particle models have been made, or how specific facts have been arrived at. Their research involved 357 pupils, age 15, who attended lessons concerning the basic aspects of the particulate model, i.e. the atom and the three main sub-atomic particles. Their teachers were instructed to stop their lesson from time to time, at convenient places and ask the pupils to write down any questions that they would like to ask about the topic. No other part of the lessons was changed because of the investigation: the teachers planned their lessons in the normal way. The following examples of pupils' questions indicate that reasons for taught assumptions or facts remained unclear.

> How do they know that the electrons' mass is 0.000...91 kg if there aren't machines to measure it?
> Why is it that the atom has a round shape and not a different one?
> What is the colour of atoms?
> Why do empty spaces exist between particles?
> Why does the atom exist?
> How can people know that atoms exist if they cannot be seen or felt?
> How was the atom discovered?
> What is the reason for such a variety of atomic models? (Maskill & Pedrosa de Jesus, 1997 a, p.132-133)

In a similar investigation for the topic of "heat, energy and temperature", involving 183 pupils, age 15-16, it was found that:

> "...the large majority of questions, 85 per cent, were not founded upon alternative frameworks, but stemmed from a need for better and clearer explanations of the logical interconnections in the subject. It is suggested that the logical organisation of the subject would, overall, be a better basis than alternative frameworks for teaching this topic." (Maskill & Pedrosa, 1997 b, p.781)

In a problem posing approach the organisation of the subject is intended to be such that it is logical to pupils, as a result of content specific motives that are raised and fulfilled. In this way, pupils seem to be better able to actively participate in the construction of knowledge and therefore better able to appreciate the reasons for specific hypotheses. Possibly, some of the questions that have been found by Maskill and Pedrosa de Jesus can even be used productively in the development of a problem posing approach, such as:

What size can atoms be?
How is it possible to weigh atoms?
Why is it that during a phase change the temperature remains the same (..) ?
Why do some substances absorb heat better than others?
Can we see the particles moving, if we put a piece of wood in the microscope?
Why does an increase in temperature imply an increase in the movement of the particles?
Why is it that the particles in a body are in permanent movement? (Maskill & Pedrosa, 1997 a/b)

Finally, because of the specific motives that encourage pupils to make specific assumptions that were intended by the designer, it seems possible to really involve pupils in a modelling process. Several pupils in our approach argued that, because the model was the result of their own thinking, they were better able to understand it. Furthermore, the results of our research indicate that pupils are indeed quite able to apply and develop a model and that they enjoy being involved in such a process. Learning about modelling thus not so much consists in learning new modelling skills, but in wanting to use their ability to reason in new situations and with new knowledge. Therefore, in our opinion, adequate teaching about modelling foremost consists in raising an adequate general motive and in making pupils reflect, at appropriate instances, at their own explanations in order to make the general framework of the model explicit. Such a framework may then guide subsequent modelling activities. In addition, pupils seem to need help when evaluating their intuitive comparisons of hypotheses. Such interventions, as well as reflection on the modelling process itself, may further develop pupils' ability to reason with the model, and with new knowledge in general.

In summary, it is concluded that most of the content specific choices still seem to be adequate, but some suggestions for improvements are appropriate. These mainly concern the way in which:
- the initial theoretical orientation may be induced;
- pupils may arrive at the correspondence between the temperature of a gas and the speed of the particles;
- it may become worthwhile to pupils to reflect on the general framework and the invariant nature of the particles.

In addition, the "basic ideas" presented in the third chapter also still seem adequate for the topic of particle models. Especially the problem posing idea is considered worthwhile because it makes it possible for pupils to understand why specific hypotheses are made and to be involved in the modelling process themselves.

6.4.4 The emergence of a structure

The previous two sections contain a detailed evaluation of the choices that have been made during the development of the approach and of what can be achieved by means of such an approach. In this section, the previous evaluation is reflected upon in order to show the main characteristics of the approach and how these are connected. An important aspect of the approach is its problem posing character, i.e. our attempt to provide pupils with motives for extending their knowledge in the direction that we intended. In retrospect, it seems that because of this problem posing character, the two main content-specific aims, i.e. learning to insightfully use a particle model in explaining macroscopic behaviour of matter, and obtaining insight in the nature of particle models and scientific modelling, have not only been worked at in relation to each other, but more strongly, in dependence of each other. Teaching and learning about the nature of the model not only takes place by means of reflection on this model, but at several instances, issues concerning the nature of particle models, or of physics in general, also raise a motive for further investigation of the model itself. We suggest that it is this close connection between the model and the nature of the model, as well as the general and local motives that emerge from and contribute to development of these issues, that enable pupils to take an active and worthwhile part in the process of modelling.

The problem posing character and the interdependence of the content specific aims are visualised in the main outline which is shown in figure 6.1. This structure is written in the form of three columns. The left one consists of knowledge of physics and the right one of knowledge of the nature of physics. These two columns are therefore related to the above stated aims. The arrows show how the process of teaching and learning switches between columns and how these switches do naturally come forward because of motives that are developed. These motives constitute the middle column.
This structure has not been developed beforehand, but has been obtained as a result of reflection on the suggested improved approach. In this structure, one can also read a succession of six phases in the process of teaching and learning, where each motive marks a transition from one phase to the next. We characterise the phases by their functions, as follows:

1. Evoking a global interest in the topic at hand.
2. Narrowing down this global interest into a content specific global motive.
3. Extension of pupils' existing knowledge in a restricted setting, which is directed by the global motive and eventually results in a need for reflection on the extended knowledge.
4. Reflection on the knowledge developed so far, in light of the global motive, resulting in a suspicion of a fruitful further extension of this knowledge.
5. Extension and modification of the knowledge developed so far, by widening the range of application, which eventually results in a need for reflection on the method of working.
6. Reflection on the method of working, in relation to the nature of the global motive, which also provides an initial outlook on subsequent learning.

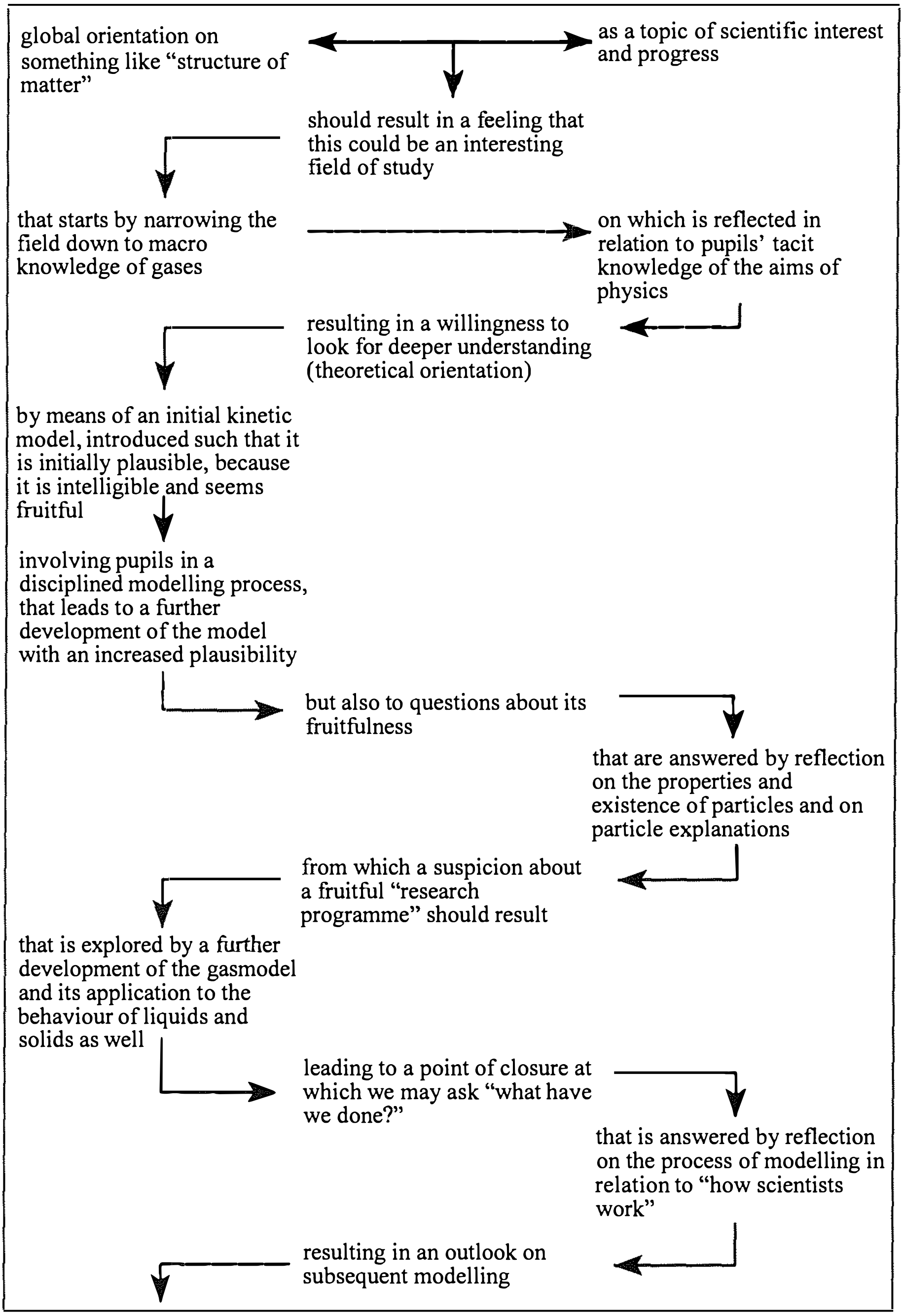


Figure 6.1 The structure of our approach.

Within many of these phases, at a more detailed level, the process of teaching and learning also switches between the left and the right column. As such, the structure is very schematic. For instance, the course of the process during the third phase is more complicated than is illustrated in fig.6.1: the hypothetical nature of the model that has just been introduced is expected to become more apparent when several ways to connect the temperature of a gas to the model seem plausible, and as such induces a local motive to further develop the model; in turn, already during the subsequent process of further development in this phase, a motive to reflect on the explanations given is induced. The above structure is also somewhat idealised, moreover. For instance, we have not yet succeeded in making the transition to the sixth phase sufficiently problem posing.

6.5 Closing remarks

In this final section of the thesis our problem posing approach is reflected upon in order to make suggestions concerning teaching and learning physics in general.

Comparison to other approaches

Having available the structure presented above, we can discuss the main differences with other strategies. In section 3.2, at a general level, two kinds of teaching strategies have been discussed, i.e. those that make use of cognitive conflict and those that attempt to develop those ideas of pupils that are more or less in agreement with the school science view. As has been argued before, both kinds of strategies seem to be based upon the idea that many of pupils' existing ideas about physics topics are incorrect and need to be changed. It has also been argued that we consider such an approach inadequate because there are several indications that pupils' prior knowledge may be limited, but otherwise largely correct. In addition, as compared to our own structure, many of these strategies barely emphasise content specific reasons for pupils to be involved in the activities and to develop specific new knowledge. For instance, the general strategy of Driver and Oldham (1986) mainly recommends to involve pupils in a comparison with the alternative, possibly conflicting, views of others, to point out inadequacies in their reasoning and to expose them to "surprise" demonstrations. Subsequently, pupils are encouraged to evaluate the alternative views and eventually the teacher presents and explains the school science view, providing opportunities to "construct meaning for it" (Driver & Oldham, 1986, p.118). What fails, in our opinion, is the recommendation to design a content specific outline of important subsequent steps that pupils need to take in order to arrive at the knowledge that is aimed for, and of suitable motives and activities that will encourage pupils to indeed take these steps. Furthermore, in comparison to our own structure, the strategy of Driver and Oldham does not indicate how, and at which stages, aspects of the nature of physics can be incorporated. As a result, activities dealing with such aspects were not sufficiently integrated in their specific "approach to teaching the particulate theory of matter" (CLIS, 1987), and we think that therefore pupils did not see the point of being involved in them.
The approaches of Meheut et al. (1990, 1994, 1995) and of Séré (1990, 1992) are quite different. These neither attempt to elicit prior ideas nor provoke a cognitive conflict. Instead, while building on previously developed knowledge and/or intuitions of pupils, these researchers aimed to investigate to what extent pupils were able to reason with new knowledge

that was offered. As a consequence, the structure of their strategies seems to be much more established and explained on content specific grounds. However, in both strategies, several pieces of new knowledge are presented without first bringing pupils in such a position that they themselves can understand the reasons for incorporating these aspects. Which, in turn, not only increases the chance that pupils do not sufficiently understand these aspects, but may also implicitly confirm a naive view of physics (cf. sections 2.2.4 and 2.3.5).
Our own approach is very much based upon content specific choices. As a result of these choices, it appears possible to successfully build on pupils' existing and largely correct knowledge and intuitions. In that respect, the approach clearly differs from conceptual change strategies, and is more in line with those of Séré and Meheut. Without devaluating pupils' prior knowledge, our strategy attempts to encourage pupils to develop appropriate new understandings. However, more than in the approaches of the latter, it is attempted to make each aspect of this new knowledge, or each step in the process of arriving at this knowledge, worthwhile to pupils. As argued previously, the development of such an outline demands a thorough content specific analysis of the physics topic, as well as developmental research. In such an outline, terms from conceptual change theories, such as "intelligible", "plausible" and "fruitful", may still function quite well (cf. fig.6.1), because these terms do not refer to a cognitive conflict as such, but to the knowledge that is presented and applied.
Furthermore, whereas in the literature much is written on the need of reflection on contents and on learning processes in order to promote the development of both pupils' conceptual understanding and their knowledge about the nature of physics, it mostly remains unclear how this should be put into practice. The approaches discussed above have not succeeded to productively integrate such reflective activities in the teaching process. Based upon our research, we suggest that the structure presented in the previous section may solve both problems in the case of teaching about particles. Which leads to the question to what extent this structure can be generalised to the teaching of other topics of physics, or maybe even to the teaching of other topics of science.
In answering this question we first have to realise that the above structure itself is still written in content specific terms that deal with the topic of particles. We have tried to characterise the phases that can be read in this structure in terms that no longer refer to particles, however. We suppose that the succession of such phases, i.e. phases with these functions, may be of a more general use. We will not extensively discuss this conjecture, but just make a final comment. As said before, we distinguish between motives that ask for a practical orientation and motives that demand a theoretical orientation. When, in a problem posing approach, one has to do with a theoretical orientation, as in the case of particle models, the suggested interdependence between teaching physics contents and, by reflection, teaching about the nature of physics contents and of scientific work, comes forward quite naturally. When one has to do with a practical motive, this particular interdependence may be less natural. The succession of phases may however still be of value, although most likely the reflective phases will have a different function, such that an interdependence of a different kind may come forward. We leave these matters here for future research.

Comparison to the present reform of advanced level education in the Netherlands

Presently, advanced level education in the Netherlands is being reformed considerably. The basic principle underlying this extensive reform is that pupils need to become more actively involved in the process of teaching and learning and, consequently, that the teacher's role changes from lecturing towards guiding pupils' development of knowledge and skills.

At this general level, our approach to teaching and learning an introductory particle model seems to fit very well in this new policy.
However, the actual way in which these plans are presently carried out by many schools shows an emphasis on general educational goals and methods, irrespective of the contents of subjects and topics. It seems that in these schools the most important goal is to arrive at a situation in which pupils work and learn independently. That means that it is not simply intended for pupils to independently make exercises or perform experiments considered important by the teacher. In addition, by means of such activities, and by reading their textbooks and using modern sources of information, pupils are expected to independently extend their knowledge. In this setting, the teacher provides them with instructions such as when to have finished which part of the book, corrects their output and explains individually to pupils.
We fear that such a reform may not be an improvement, and instead may lead to situations in which pupils are less motivated to learn and in which their learning process is not sufficiently meaningful. Pupils cannot be expected to automatically become actively involved in a meaningful way simply by forcing them to perform the above activities. For instance, reading texts, even by means of modern sources, can be far less enjoying than listening to fascinating explanations by a teacher. Furthermore, actively making sense of such texts may be even more difficult than trying to understand the teacher. Instead, the present educational reform most likely only results in considerable improvement when intended changes are based on content specific choices. In order to make pupils actively involved in a meaningful process of teaching and learning, it is recommended to provide them with motives to construct new knowledge. In addition, at appropriate stages, the teacher needs to initiate and carefully guide reflection and/or subsequent learning, for pupils cannot always be expected to take important steps in the conceptual development all by themselves. For instance, in our approach to teaching and learning a particle model, pupils most likely are capable of developing several hypotheses independently, but they cannot be expected to arrive at invariant particles as a basic and worthwhile principle without the help of the teacher. When such an improved setting is provided, pupils may be more able and more willing to learn independently. Moreover, they may take more responsibility for their own learning process, for they can appreciate why it can be worthwhile to extend their knowledge in a specific direction and new understandings are established on grounds that they themselves can understand.

The image of physics

It is often argued that the physics curriculum in secondary education should contain more modern physics, or at least more fancy contemporary applications. The "old" physics is considered too dull, which in turn may cause less pupils to choose to study physics in upper secondary and higher education. The physics incorporated in our approach to teaching and learning a particle model has been developed completely by scientists in previous centuries. Moreover, no fancy applications were included in the scenario. Nevertheless, the pupils involved in our research did not seem to consider the physics contents dull. Instead, they seemed to enjoy being able to develop the model themselves and having some idea of how this knowledge was constructed in history. Although the image of physics is most likely improved if appropriate modern applications are included in the curriculum, it is at least as important to challenge pupils by means of interesting problems which they can and want to solve. This recommendation is illustrated by the following recent contribution to the discussion concerning the image of physics, written by a pupil in her final year of the highest level of upper secondary education (H. Meeus, letter in NVOX 1998 (23) 6, p.343):

> [Concerning the physics lessons she attended in lower secondary education:]
> For one moment, we were the earliest scientists, who asked themselves questions and who wanted to know how and what and most of all why? Just like those first scientists we also conducted research. We received models and books for this. That was our research. Finally, it was as if you invented the three laws of Newton yourself. That was satisfying. (...)
> [Concerning physics lessons in upper secondary education:]
> In the fifth grade it changed. We received books filled with formulas, but I had not yet asked myself any questions at all, for I did not get the chance to do so. Phenomena were explained by means of numbers. The order changed to: formulas, explanations (research was skipped) and finally questions. When I asked: Why? I received the answer: Just watch, when you put this in the formula, then that is the result. That is why. (...) The phenomena that we are trying to explain are not only very remote (leptons, isomers) - which does not have to be a problem - but are also presented in such a way that you get the feeling: What am I doing? (...)
> First, people should think about the way in which exact sciences can mean something to pupils. (...) an approach that starts with asking questions instead of ending with them.

The questions referred to by this pupil in her final recommendation are not questions which emerge because pupils do not understand the teacher's explanation (such as found in the research of Maskill and Pedrosa, 1997 a/b), nor questions used in textbooks as a means to check whether pupils have understood the contents. Instead, these are questions that pupils raise, or at least can come to find important, exactly because they understand the knowledge that has previously been taught. A problem posing approach attempts to raise such question and to provide pupils with a means to develop new knowledge in order to answer them. As such, we therefore expect that this approach can contribute to an improved image of physics.

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Appendices

Appendix A

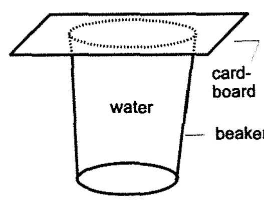
Worksheet of activity 4

During the class discussion you have seen how you can ask new questions about known regularities. And how you can answer such a question by means of the model of balls. In this worksheet you are going to consider more of such known regularities, and to try to also frame new questions about these. Try to answer the questions that you frame by means of the model of balls.

Experiment 1

A beaker, filled with water, is shut by means of a piece of cardboard (see drawing). Subsequently, the beaker, with the cardboard on it, is held upside down.

a) What will happen after it is held upside down?
   Always when this beaker is held upside down.....



experiment 1

b) By means of which more general regularity can you come to a better understanding of this?

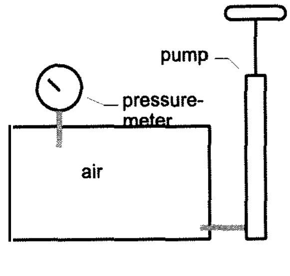
c) Can you frame a question about this, to which you do not yet know an answer? Which question?

d) Try to answer this question by means of the model of balls. If air behaves just like a collection of moving balls I can understand this, for.....

Experiment 2

A closed container, filled with air, is connected to a pressure meter (see drawing). Subsequently, extra air is pumped in, until the total amount of air in the container is exactly three times as much.

a) What exactly will happen to the air pressure?
   Always when the amount of air in this container becomes exactly three times as much.....



experiment 2

b) More general regularity:

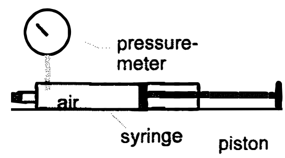
c) Question:

d) If air behaves just like a collection of moving balls I can understand this, for.....

Experiment 3

A closed syringe, filled with air, is connected to a pressure meter (see drawing). The piston of the syringe is pushed in until the volume is exactly 1/3 of the original volume.

a) What exactly will happen to the air pressure?
Always when this piston is pushed in until the volume is exactly 1/3.....



experiment 3

b) More general regularity:

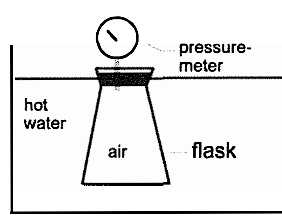
c) Question:

d) If air behaves just like a collection of moving balls I can understand this, for.....

Experiment 4

A closed flask, filled with air, is connected to a pressure meter (see drawing). The flask is heated (in hot water) until the absolute temperature is exactly 1 ¼ as high.

a) What exactly will happen to the air pressure?
Always when this flask is heated until the absolute temperature is exactly 1 ¼ as high.....



experiment 4

b) More general regularity:

c) Question:

d) If air behaves just like a collection of moving balls I can understand this, for.....

Example of the worksheets of activity 7: mass

Problem

We do not know yet how to explain that when the TEMPERATURE of an amount of gas is rising (at constant VOLUME), the PRESSURE of the gas also increases.

When we compare the gas to a collection of moving balls, we must find a way by means of which the force, exerted by the balls due to collisions, increases.
Suppose that the *mass* of the balls increases. Would this solve the problem?

Discuss this with your group. Try to reach an agreement on the following issues.

When the *mass* of the balls becomes three times as large:
- will they collide with the wall more often? if they do: how much more often?

- will they collide with more impact? if they do: with how much more impact?

- will the force that they exert by means of their collisions increase? why / why not?

* If your group decides that the force, in this case, does <u>not</u> increase, then a bigger *mass* of the balls cannot be the solution to our problem. Try to think of another possible solution and answer the above questions again (so: substitute *mass* by something else).

* If your group decides that the force, in this case, <u>does</u> increase, then a bigger *mass* of the balls might be the solution to our problem. Try to investigate this a little further:

- can you think of any objections to the comparison of the TEMPERATURE to the *mass* of the balls?

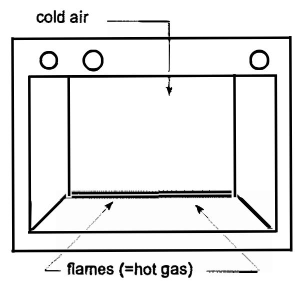
- suppose that air really is a collection of moving balls and that the *mass* of these balls is bigger at a higher TEMPERATURE, what will happen to an amount of air if you make it very hot or very cold?

Worksheet of activity 9

Problem

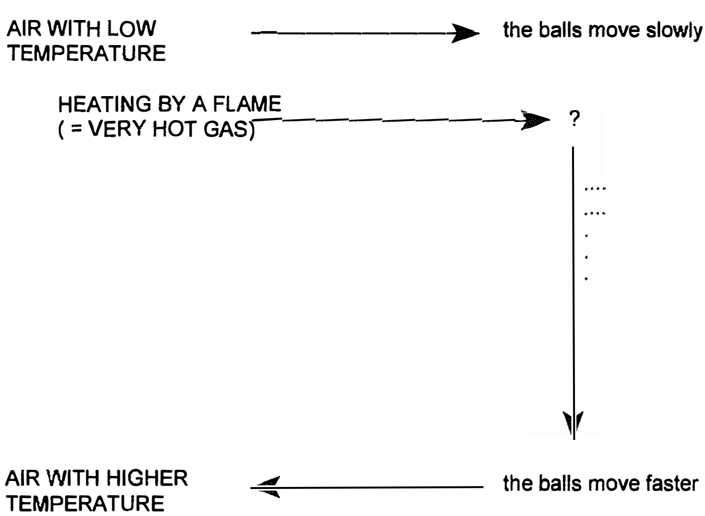
We have assumed that a gas that is rising in temperature can be compared to a collection of balls whose speed is increasing. But how can these balls come to move faster?

In this worksheet you will try to find an answer to this question.



Imagine the working of a hot-air oven. When you light the gas, by using a match, flames appear. A flame is actually a very hot gas.
If we compare this hot gas to a collection of balls, then we must assume that these balls are moving very fast.
The air in the oven is heated by the flames. If we compare the air in the oven to a collection of moving balls as well, then we must assume that *these balls are somehow going to move faster*. How can this be?

Try to think of an explanation. Complete the diagram below by writing down, step by step, what will happen to the balls.



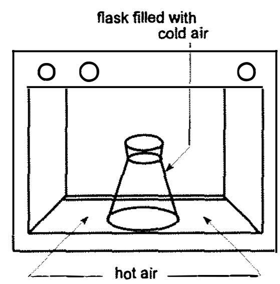
Can you now give a possible answer to the following question:
How can the balls come to move faster?

Example of the worksheets of activity 10: heating by means of hot air

Problem

We have assumed that a gas that is rising/decreasing in temperature can be compared to a collection of balls whose speed is increasing/decreasing. But how can these balls come to move faster or slower?

You already thought about this problem in the situation in which an amount of cold air is heated in an oven. But there are still other ways to increase the temperature of an amount of gas. In this worksheet you will think about this.



If a closed flask, filled with air, is heated in a hot-air oven, then the temperature of the air in the flask will rise.
If we compare the air in the closed flask to a collection of moving balls, then we must assume that, because of contact between the flask and the hot air outside, *the balls in the flask are somehow going to move faster*. How can this be?

Try to think of an explanation. Complete the diagram below by writing down, step by step, what will happen to the balls.

THE FLASK CONTAINS AIR WITH A CERTAIN TEMPERATURE → the balls move with a certain speed

HEATING BY HOT AIR (OUTSIDE THE FLASK) → ?

....
....
.
.
.

THE AIR IN THE FLASK HAS A HIGHER TEMPERATURE ← the balls move with a greater speed

* Imagine that the flask, filled with hot air, is put in a freezer. Can you now understand, by means of the model of balls, that the air in the flask becomes colder?

* Can you now give a new answer to the question: How can the balls come to move faster or slower?

When you all agree on the results, write these down on the poster.

Example of the worksheets of activity 10: bicycle pump

Problem

We have assumed that a gas that is rising/decreasing in temperature can be compared to a collection of balls whose speed is increasing/decreasing. But how can these balls come to move faster or slower?

You already thought about this problem in the situation in which an amount of cold air is heated in an oven. But there are still other ways to increase the temperature of an amount of gas. In this worksheet you will think about this.

When you pump up a tyre (or something else) by means of a bicycle pump, you push the piston inwards. While doing this, the VOLUME of the air in the pump decreases and the PRESSURE increases. When you do this very fast, the air in the pump becomes warm (the TEMPERATURE of the air rises), even when there is no friction between piston and pump.

If we compare the air in the pump to a collection of moving balls, we have to assume that because of pushing the piston inwards, *these balls are somehow going to move faster*. How can this be?

Try to think of an explanation. Complete the diagram below by writing down, step by step, what will happen to the balls.

PRESSURE → Total force that the balls exert by means of their collisions against the wall

VOLUME → Space in which the balls move

TEMPERATURE → Speed of the balls

PISTON DOWNWARDS VERY FAST → ?

....

....

.

.

.

↓

HIGHER TEMPERATURE ← Higher speed of the balls

SMALLER VOLUME ← Smaller space in which the balls move

LARGER PRESSURE ← Larger total force that the balls exert by means of their collisions

* Can you now also explain, by means of the model of balls, how a small amount of hot air in a syringe can cool down?

* Can you now give a new answer to the question: How can the balls come to move faster or slower?

When you all agree on the results, write these down on the poster.

Aid to one of the worksheets of activity 10: bicycle pump

When the piston is slowly pushed downwards, the VOLUME of the gas decreases and the PRESSURE increases. The TEMPERATURE does not change.

If we compare this to the behaviour of a collection of moving balls, the following happens to the balls.

PRESSURE → Total force that the balls exert by means of their collisions against the wall

VOLUME → Space in which the balls move

TEMPERATURE → Speed of the balls

PISTON DOWNWARDS → Space in which the balls move decreases

↓ They collide more often (but are not going to move faster)

↓ The total force that the balls exert by means of their collisions increases

SAME TEMPERATURE ← Same speed of the balls

SMALLER VOLUME ← Smaller space in which the balls move

LARGER PRESSURE ← Larger total force that the balls exert by means of their collisions

When the piston is pushed downwards very fast, the space in which the balls move decreases very fast, but meanwhile something else happens, because of which the balls obtain a higher speed. What could that be?

PISTON DOWNWARDS VERY FAST: space in which the balls move decreases and...?

Worksheet of activity 13

Problem

Would a gas really be a collection of moving and colliding balls?

You already answered many questions and came to a better understanding of several phenomena by means of the model of moving balls. So maybe a gas really is a collection of moving balls. But when you look at a gas, for instance the air around you, you do not see moving and colliding balls. Maybe they can be seen through a microscope.

* Use a microscope to look at air. Can you see moving and colliding balls?

Imagine that you add some smoke of a cigarette to the air in the container. Smoke consists of tiny bits of ash, which can be seen under a microscope as tiny illuminated spots.

* If air really was a collection of invisibly small, colliding balls and you added a few visible bits of ash: what would you then expect to see under the microscope? What would happen to these bits of ash? Discuss this with your group and try to agree on a prediction. Explain your prediction by means of a drawing.

* Use the microscope to look at bits of ash in air. What do you see?

  Did your prediction come true?

  If air really is a collection of colliding balls, can you then explain your observations?

  Can you also explain this if air is not a collection of colliding balls? If you can, what is the explanation?

In this lesson we try to answer the following question:

Could it be that a gas really is a collection of moving balls?

* Discuss this with your group:
  What use is the experiment in answering the question?
  Could the outcome be a new indication?
  If so, why? What did you find out?
  And how important do you think this indication is?

* What is your answer to the main question of this worksheet?

* Did you come up with any new questions that you cannot answer yet?

Example of the worksheets of activity 16: ongoing motion

Problem

If a gas really is a collection of moving and colliding balls, how can it be that these balls keep on moving? And what is there between them?

You might have asked yourself how it can be that the balls of a gas always continue to move. After all, if you imitated the model with marbles, these would not keep on going forever. If you want them to go on, you need to push them again and again. But in a gas there is nothing that pushes the balls.
Then how can it be that the balls of a gas keep on moving?

In the following examples you will investigate how well the model is imitated. When you have found the best simulation, you might be able to say more about the circumstances that are necessary in order for the balls to keep on going.

Imagine a box which can be closed. In this box you put some balls. Then you close the box and shake it up and down. *After you stop shaking, which kind of balls, mentioned below, will keep going for the longest time?*

a. balls of chewing gum
b. ping-pong balls
c. rubber balls
d. ball-bearings
e. cooked peas
f. balls of clay

Explain your answer.

Imagine the same box. In this box you put the balls that you have chosen above. Now we will vary what they move in. *After you stop shaking, in which of the below cases will the balls keep going for the longest time?*

a. air
b. water
c. rarefied air
d. syrup
e. nothing
f. compressed air

Explain your answer.

If a gas really is a collection of moving balls, what can these balls best be compared to?

And in what will they probably move?

Worksheet of activity 19

In the class discussion you have already seen that there are specific similarities in the behaviour of gases, liquids and solids. These similarities indicate that the model of balls can also be used to better understand the behaviour of liquids and solids.
But there are also important differences, for a gas is not exactly the same as a liquid or a solid. You can take these differences into account by considering how you can change the model a little. By means of the new model you can then understand both the behaviour of gases and the behaviour of liquids and solids.

Below, a difference between gases, liquids and solids is mentioned. *If you know any more you can add these.*

1. Gases always spread out as much as possible. Liquids and solids do not. Why not?

2. .....
   .....
   .....

Now try, together with your group, to extend the model, so that it can also be used to better understand the behaviour of solids and liquids. Can you understand the above differences by means of that model?

Maybe you have thought of two or more ways to change the model. If you cannot yet agree on the best change, think of a way to proceed so that you will come to an agreement.

Describe your extended model below, or explain what you will do in order to come to an agreement.

Worksheet of activity 20

(=the back of the worksheet of activity 19)

Now frame questions about known regularities in the behaviour of solids and liquids, like you did in the first lesson concerning gases. *Try to answer these questions by means of your model.*
If there are some questions that you cannot yet answer appropriately, then it may be that your model is not yet good enough. *In that case, think about how to improve the model.*

MAKE NOTES OF ALL YOUR QUESTIONS AND ANSWERS!
These can be used during the conference.

Examples of questions that you could pose and answer:

- -why does a gas become liquid when it is compressed very much?
- -why does a gas become liquid and a liquid become solid when it is increasingly cooled?
- -why does a liquid evaporate at room temperature?
- -why does each substance have its own boiling-point / melting-point (which differs from other substances) ?
- -?

Activity 20: examples of phenomena

A beaker filled with water: surrounding air is removed

If you close a plastic bag, filled with air, and remove the surrounding air, the bag becomes bigger.
If you fill a beaker with water, and remove the surrounding air, what will happen? Can you frame a prediction by means of your model of balls?

The ball and the ring

A specific metal ball exactly fits in a specific metal ring. If the ball is heated, it expands and no longer fits in the ring. Because of the contact between the ball and the ring, the latter also becomes warm and after some time the ball fits in the ring again: the ring has also expanded.
Why does the ring, during heating, only expand outwards and not inwards? Can you understand this by means of your model of balls?

Mothballs

Some solids you can smell. That means that they are partly evaporated. How can solids evaporate? Can you understand this by means of your model of balls?

Crystals

Some solids are built very regularly. During the change of state from liquid to solid, apparently something special happens, because of which a crystal emerges. Can you understand this by means of your model of balls?

Boiling: heating without temperature rise

During boiling, and also during melting, the temperature stays the same, while you do add heat. So the balls of the substance are not going to move faster, while they do collide with faster moving balls. How can that be?

Homework following activity 20

Robert Brown

This is the story of an English botanist. His name was Robert Brown, and he was born in 1773, in Scotland. After secondary school he began to study medicine at the university of Edinburgh. Already at secondary school, and later also at university, he spent all his free time studying plants.
He did not finish his study at the university. Instead, he joined the army. Until, in 1800, he was asked to go on an explorative expedition along the coasts of Australia. During the next four years he studied all kinds of plants and brought over four thousand different species back to England. Most of these were unknown until then. In England, he became the administrator of an important library in the field of botany and, as such, he could continue his research on new species.

In 1827 Robert Brown was investigating the shape of specific grains of pollen. He put these grains in water and examined this by means of a microscope. Very clearly he could see that the grains moved chaotically. After many repeated observations, Robert Brown was convinced that this movement could not be caused by flow of the liquid, nor by a gradual evaporation. The grains thus had to move by themselves and therefore he called them "active molecules".

Based upon his observations, Brown developed a theory: probably pollen of all living plants consist of active grains which move by themselves. He started to investigate this and his theory was confirmed! For all the plants of which he investigated the pollen, he saw the grains move vividly by themselves.

Assignment

You have just learnt about matter in school and you have developed your own model. Write a letter to Robert Brown in which you explain what you think of his theory. Explain, as well as possible, what your model looks like and how you would explain his observations. Try to convince him of your theory (so: explain why your theory is better than his). Maybe you can even provide him with some examples of new experiments that he could perform and which will show that your theory is better.

Appendix B

IME Software's Gassim page http://www.ozemail.com.au/~imesoft/gassim.htm

Gassim

A molecular simulation program for demonstrating aspects of kinetic theory and statistical mechanics.

An understanding of the microscopic behaviour of a system often leads to greater insight and understanding of its macroscopic properties. Gassim simulates the motion of up to 1000 hard "2D spherical" molecules or one or two different species and brings the microscopic world of an ideal gas to life with rapid simulations that will catch the interest of classes at all levels. Adds interest to topics such as kinetic theory, equipartition theorem, diffusion, mean free path, Brownian motion, Maxwellian speed distribution, entropy, work and more.

Some of Gassim's features include:

- Optimised for speed. Approx 5 updates of 1000 molecule postions in 1 second on a Pentium 75.
- Easily adjust parameters such as:
  - Molecular size
  - Molecular mass
  - Kinetic energy
- Display speed, velocity, energy or position distributions
- Display pressure, Mean kinetic energy, entropy etc as functions of time
- Examine microscopic properties such as mean free path etc.
- Let two systems interact via a piston
- See the effects of gravity on the vertical distribution
- Set up simulations to illustrate diffusion, viscosity effects and Brownian motion
- See the effects of randomising walls on viscosity in a tube
- Comprehensive help facility
- Example simulations supplied

System requirements:

- IBM 386, 486 SX (co-processors essential) or 486 DX or Pentium
- Windows 3.1 or later with 4Mb of Ram and mouse
- Approximately 600kb of hard disk space
- VGA with better than 640x480 resolution

For systems less than 486 DX-33 a maths co-processor is essential.
Minimum recommended system is 486 DX-33 with VGA resolution of 640x480 or higher.

Appendix C

Questionnaire

During the past nine lessons you worked on the topic of "Matter". As you know, these lessons were observed, because your class worked on this topic in a special way. Therefore, we are interested in your experiences with it.
That is why we ask you to describe how you worked on "Matter". For instance:

- What did you learn during these lessons?
- Did you learn much or not?
- What is the most important thing that you learnt? What did you consider unimportant?
- As a result of this sequence, are there things that you now think about differently?

- What did you enjoy and what not?
- What did you consider good and what bad?
- In your opinion, what should be improved or handled differently?
- What do you think of the lessons as compared to other physics lessons that you have attended this year?

Appendix D

Interviews

1 The model of balls (10 minutes)

- Give a summary of the model that you have developed.
- A macroscopic description of heating is given: solid, increase of volume, melting, liquid, increase of volume and evaporation, boiling.
  Describe this whole process as detailed as possible by means of the model of balls.
- Describe all that you have learnt about the balls during the lessons.

- Why are these kind of models used? What is the purpose of it?
- How is an explanation by means of balls generally given?
- Explaining changes by means of invariant balls: what do you think of this idea? Is this worthwhile?

2 Development (5 minutes)

- If you wanted to further adjust the model, which rules would you have to obey? What should you take into account?
- In which way do you think the teacher will proceed with this in the fifth and sixth grade? Will the model be further adjusted? If so, how? (in general, not content specific)

3 Existence (10 minutes)

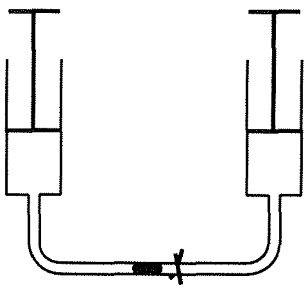
- Were you convinced, from the start, that the balls suggested by the teacher really existed?
- Did you change your opinion during the sequence? If so, because of what?
- What kind of experiences may make that you become even more convinced of the existence of such balls?

- What did you already know about molecules and atoms?
- What do you think about molecules and atoms now? Do these really exist? How do you imagine them? Are they really balls?
- What are the differences between molecules and atoms? What are the similarities?

4 Phenomena (15 minutes)

- A football is pumped full of air on a very warm day and left by itself. The football is not punctured. When you pick up the ball late at night, will the pressure of the air in the ball have changed? Explain your prediction by means of the model of balls.

- A drawing is presented of two syringes, of which the ends are connected by a tube, in which there is a drop of liquid. The piston of the left syringe is fixed.
  What happens to the drop when:
  - the piston of the right syringe is pulled upwards?
  - the piston of the right syringe is also fixed and that whole syringe is cooled?
  In both cases: when does the drop stop moving?
  Explain all your predictions by means of the model of balls.



- Explain as well and complete as possible what happens with the balls of air when you pump air in a bicycle tyre by means of a bicycle pump.
- Explain by means of the model of balls, as well and complete as possible, why ice floats on water.
- Explain by means of the model of balls, as well and complete as possible, why you can smell some substances from a distance and why some smells spread faster than others.

5 Method of working (5 minutes)

- What do you think of the way in which you worked during this sequence?
- What was different, in the way of working, as compared to other lessons:
  - in physics
  - in chemistry
- Did you always understand what each part was about and why you had to work on that, or were there activities of which you did not see the purpose?
- The sequence was structured around main questions. Have you recognised that? What do you think of such an approach?
- The teacher said a few times that in science they work in the same way. Can you explain what he meant by that?

6 Clarification of individual statements.

(different for each pupil)

7 Additional lesson

(further discussion on parts that individual pupils do not fully understand)

Samenvatting

Dit proefschrift beschrijft een onderzoek dat plaatsvond van 1993 tot 1998 in het Centrum voor Didactiek van Wiskunde en Natuurwetenschappen te Utrecht. Het betreft een vakdidactisch onderzoek naar het onderwijzen en leren van een aanvankelijk deeltjesmodel. In hoofdstuk 1 tot en met 3 worden de achtergronden van dit onderzoek geschetst. Hierin wordt duidelijk wat de specifieke moeilijkheden zijn met betrekking tot het ontwerpen van een verbeterde didactiek voor dit onderwerp. Tevens worden hierin al enige aanzetten tot een mogelijke oplossing van de problemen gegeven. Op basis van deze ideeën is tijdens het onderzoek een nieuwe didactiek ontworpen, welke in hoofdstuk 4 in detail wordt gepresenteerd en verantwoord. De toepassing van deze nieuwe benadering in de onderwijspraktijk is uitvoerig onderzocht middels observatie en analyse van het onderwijsleerproces. Hiervan wordt verslag gedaan in hoofdstuk 5. Tenslotte wordt de nieuwe didactiek in hoofdstuk 6 geëvalueerd en wordt hierop gereflecteerd. Hierin komt onder andere een didactische structuur voor het leren en onderwijzen van een aanvankelijk deeltjesmodel naar voren.

Hoofdstuk 1 begint met een korte discussie van het belang van het onderwerp "deeltjesmodellen" voor het voortgezet onderwijs in de exacte vakken. Daaruit komt naar voren dat leerlingen niet alleen over de inhoud, maar ook over de aard van dergelijke modellen zouden moeten leren. Tevens kunnen leerlingen aan de hand van onderwijs over deeltjesmodellen zelf een modelleerproces ervaren.
Vervolgens wordt in zeer globale termen uitgelegd dat het bepaald niet vanzelfsprekend blijkt te zijn dat leerlingen natuurwetenschappelijke leerstof correct begrijpen. Om het leerproces te verbeteren, is voorgesteld dat men meer rekening dient te houden met preconcepties: denkbeelden die leerlingen over het onderwerp hebben gevormd voordat zij hierover worden onderwezen. Er blijken echter weinig concrete richtlijnen te zijn voor de manier waarop dit met succes zou kunnen. Veel pogingen tot een dergelijke verbetering hebben dan ook slechts beperkte resultaten gehad.
In het Centrum voor Didactiek van Wiskunde en Natuurwetenschappen te Utrecht is een benadering ontwikkeld, welke "probleemstellend onderwijs" wordt genoemd. Probleemstellend onderwijs probeert leerlingen in een zodanige positie te brengen dat zij goede redenen ontwikkelen om hun preconcepties verder uit te breiden in de richting van de ten doel gestelde kennis. Bij de start van het onderzoek waarover in dit proefschrift wordt gerapporteerd, was deze probleemstellende benadering alleen toegepast op het onderwerp "radioactiviteit". Tegen de hierboven geschetste achtergrond is de centrale probleemstelling van het onderzoek geformuleerd als het ontwikkelen van een empirisch ondersteund onderwijsleerproces, waarin leerlingen:

- leren dat, volgens de natuurwetenschappen, materie uit specifieke deeltjes bestaat, en leren om een dergelijk deeltjesmodel te gebruiken voor het verklaren en voorspellen van diverse relevante verschijnselen;
- en de aard van deeltjesmodellen en natuurwetenschappelijk modelleren gaan begrijpen.

De uitgangspunten van dit onderzoek hebben geleid tot twee belangrijke keuzen bij het ontwerpen van een onderwijsleerproces:

- er is geprobeerd om een probleemstellende benadering te ontwikkelen;
- leerlingen hebben, onder begeleiding van docent en lesmateriaal, de mogelijkheid gekregen om zelf een deeltjesmodel (verder) te ontwikkelen, d.w.z. dat hun actieve betrokkenheid in het modelleerproces een doel op zich is geweest.

De evaluatie van het daadwerkelijke onderwijsleerproces heeft in dit proefschrift geleid tot de beantwoording van de volgende twee vragen:

1. In welke mate zijn we geslaagd in het ontwerpen van een onderwijsleerproces waarin leerlingen de gestelde doelen bereiken?
2. In welke mate ondersteunt het verloop van het onderwijsleerproces de adequaatheid van de gemaakte keuzen?

In hoofdstuk 2 worden de resultaten besproken van onderzoek naar de ideeën van leerlingen over het macroscopische gedrag en de corpusculaire aard van materie en over de aard van deeltjesmodellen en natuurwetenschappen in het algemeen. Daaruit komt naar voren dat de voorkennis van leerlingen over macroscopische verschijnselen weliswaar beperkt is, maar waarschijnlijk grotendeels correct. Onze interpretatie van onderzoeksresultaten met betrekking tot ideeën over deeltjes leidt tot de conclusie dat leerlingen bij "deeltjes" vooral aan "kleine stukjes materie" denken. In het onderwijs lijken ze vervolgens onbedoeld gestimuleerd te worden om dergelijke macroscopische brokjes materie "moleculen" te noemen. De aannames die in het onderwijs voor moleculen gesteld worden, komen echter niet overeen met hun grotendeels correcte ideeën over het gedrag van macroscopische stukjes materie. Dit leidt naar onze indruk tot veel voorkomende misconcepties over "moleculen", zoals de gedachte dat moleculen net zo veranderen als de macroscopische hoeveelheid stof, dat de ruimte tussen de moleculen niet leeg is, of dat moleculen van een vaste stof niet bewegen. In plaats van vreemde aannames te stellen over het gedrag van kleine brokjes materie, zou bij leerlingen veeleer een behoefte moeten gaan ontstaan aan deeltjes die niet precies zo veranderen als macroscopische voorwerpen, maar onveranderlijk zijn. Uit de analyse van diverse op onderzoek gebaseerde onderwijsmethoden voor de introductie van een deeltjesmodel zijn echter weinig aanknopingspunten gevonden voor de manier waarop een dergelijke behoefte bij leerlingen kan ontstaan. Bovendien kunnen we niet verwachten dat zij zelf een geschikt deeltjesmodel naar voren zullen brengen. Er zal dus een eenvoudig model geïntroduceerd moeten worden, dat vervolgens door leerlingen verder ontwikkeld kan worden in de richting van een model waarin macroscopische veranderingen verklaard worden met behulp van onveranderlijke deeltjes. De analyse van andere benaderingen voor dit onderwerp heeft enkele voorbeelden opgeleverd van axioma's die in eerste instantie bij leerlingen geïntroduceerd kunnen worden, bijvoorbeeld dat alle moleculen van één stof identiek zijn. Het blijkt echter moeilijk om deze axioma's ook plausibel voor leerlingen te maken.
De analyse van andere benaderingen heeft wel enkele aanknopingspunten opgeleverd voor het vaststellen van een geschikt model als voorlopig einddoel van het modelleerproces. Er zal onder andere ruim aandacht besteed moeten worden aan de manier waarop het model moet worden verbonden met macroscopische verschijnselen. De analyse van andere benaderingen wijst er in dit verband op dat vooral de aspecten van intrinsieke beweging en lege ruimte, en de correspondentie tussen macroscopische temperatuur en kinetische energie van de deeltjes problematisch zijn.

Tenslotte lijken de in de literatuur gerapporteerde resultaten van onderzoek naar ideeën over de aard van natuurwetenschappen het best te kunnen worden geïnterpreteerd als een naïef beeld: een vaag idee van wat natuurwetenschappers doen en bereiken, grotendeels gekenmerkt door onwetendheid. Dit beeld lijkt in het onderwijs nauwelijks verhelderd te worden. Om meer te gaan begrijpen over de aard van deeltjesmodellen, lijkt een actieve betrokkenheid in het modelleerproces als zodanig niet voldoende. Daartoe zou, meer dan gebruikelijk, aandacht besteed moeten worden aan vragen zoals voor welk doel en op welke manier een deeltjesmodel gebruikt kan worden. Ook zouden leerlingen actief betrokken moeten zijn bij het proces van testen van en kiezen voor bepaalde hypothesen, opdat ze dergelijke aannames niet als een verzameling onveranderlijke feiten gaan beschouwen. Bovendien zouden zij gestimuleerd moeten worden om te reflecteren op de aard van de deeltjes. Over hoe dit alles te bereiken valt, heeft de analyse van andere benaderingen nauwelijks aanknopingspunten opgeleverd.

In hoofdstuk 3 worden onze eigen opvattingen over leren en onderwijzen van natuurkunde, en van een deeltjesmodel in het bijzonder, uiteengezet. Ten aanzien van leren en onderwijzen wordt aangegeven dat het verstandig lijkt om leerlingen actief te betrekken bij de integratie van nieuwe informatie in reeds bestaande kennis (dit wordt in de rest van het proefschrift "het constructivistisch idee" genoemd). Hierna worden verschillende gangbare soorten "constructivistische onderwijs strategieën" besproken, en wordt uitgelegd waarom er in dit onderzoek van geen van deze soorten gebruik gemaakt kan worden. Uitgangspunt daarbij is onze opvatting dat de preconcepties van leerlingen grotendeels correct of nog nauwelijks ontwikkeld zijn. Hieraan wordt vervolgens een uitgangspunt toegevoegd, namelijk dat leerlingen gedurende het hele onderwijsleerproces steeds de zin moeten kunnen zien van wat zij aan het doen zijn. Dit uitgangspunt vormt de kern van probleemstellend onderwijs. Als hieraan is voldaan, mogen we verwachten dat nieuwe kennis niet geforceerd aan leerlingen wordt opgedrongen, maar dat zij deze zullen accepteren op gronden die zij zelf begrijpen. Hoewel dit laatste uitgangspunt triviaal lijkt, blijkt het moeilijk in praktijk te brengen. Daartoe probeert de ontwerper om leerlingen steeds inhoudelijke motieven te verschaffen voor de uitbreiding van hun kennis, namelijk door via goed doordachte activiteiten bepaalde problemen bij leerlingen op te roepen. Idealiter zouden leerlingen deze bedoelde problemen als hun eigen problemen moeten gaan zien en zouden de activiteiten zodanig moeten zijn dat leerlingen zelf kunnen inzien hoe deze hen zullen helpen bij het zoeken naar een oplossing.
Door specifieke problemen op te roepen en leerlingen adequaat hulp te bieden bij het zoeken naar oplossingen wordt gepoogd om inhoudelijk richting te geven aan het integreren van nieuwe natuurkundige inzichten in de bij leerlingen reeds bestaande kennis. Tegelijkertijd worden leerlingen hierdoor actief in het modelleerproces betrokken zodat zij niet alleen kunnen leren hoe het deeltjesmodel kan worden toegepast, maar ook waarom bepaalde aannames worden gesteld en hoe deze getest kunnen worden.
Het ontwerpen van een probleemstellende benadering is niet eenvoudig. Het vereist niet alleen een gedegen inzicht in de reeds bestaande kennis van leerlingen maar ook een vermogen om zich voor te stellen hoe leerlingen bepaalde problemen interessant kunnen gaan vinden, wat zij een voor de hand liggende manier zullen vinden om aan een probleem te werken en hoe zij het best gestuurd kunnen worden in het zoeken naar een oplossing. Het lijkt derhalve verstandig om tijdens het ontwerpen en verbeteren van een reeks activiteiten regelmatig te onderzoeken in hoeverre verwachtingen over het verloop van het onderwijsleerproces terecht blijken te zijn. Daartoe is het noodzakelijk dat deze verwachtingen zeer precies

worden beschreven en verantwoord. Dit gebeurt in de vorm van een scenario. De empirische resultaten van het testen van het scenario worden vervolgens gebruikt om het ontwerp verder te verbeteren. Aangezien het in dergelijk ontwikkelingsonderzoek belangrijk is om het proces in de klas in detail te analyseren, is er gebruik gemaakt van kwalitatieve onderzoeksmethoden in een kleinschalig project: observaties en interviews met één ervaren natuurkunde docent en, per onderzoeksronde, één klas (twee in totaal; 4-havo/vwo).
Op basis van een beknopte analyse van de kenmerken van klassieke deeltjesmodellen wordt in het vervolg van hoofdstuk 3 uiteengezet welk deeltjesmodel in onze benadering als leerdoel wordt gesteld en hoe dit aansluit bij vervolgonderwijs over deeltjesmodellen. Dit model bestaat uit onveranderlijke deeltjes die voortdurend bewegen in lege ruimte. Hun bewegingen worden bepaald door aannames over hun interacties: elastische botsingen en onderlinge krachten. Aan de hand van dit model zal tijdens het modelleren een algemeen kader voor deeltjesverklaringen ontwikkeld moeten worden, waarin naast de onveranderlijkheid van de deeltjes ook het nodig zijn van twee hypothesen wordt benadrukt: hypothesen over het gedrag van de deeltjes en hypothesen over de correspondentie tussen model en macroscopische grootheden. Daar een deeltjesmodel beter vanuit een theoretische oriëntatie dan vanuit een praktische geïntroduceerd lijkt te kunnen worden, zal de lessenserie over deeltjes zodanig ingericht moeten worden dat leerlingen het zinvol gaan vinden om eerder vastgestelde generalisaties met betrekking tot macroscopisch gedrag van materie beter te gaan begrijpen.
Aan het eind van hoofdstuk 3 worden, op basis van het voorgaande, globale keuzen met betrekking tot het ontwerp van de nieuwe benadering verantwoord. Om bijvoorbeeld de aanname van onveranderlijke deeltjes gaandeweg voor leerlingen zinvol te laten worden, is ervoor gekozen om in het model dat geïntroduceerd wordt al direct te spreken van bewegende deeltjes. Om deze voortdurende beweging vanaf het begin voor leerlingen zinvol te laten zijn, wordt het model naar voren gebracht als een hulpmiddel bij het beter gaan begrijpen van druk verschijnselen van gassen. Verder is ervoor gekozen veel aandacht te besteden aan de naar verwachting problematische relatie tussen de temperatuur van een macroscopisch object en de snelheid van de deeltjes. Naar verwachting wordt het daarna eenvoudiger om aspecten als onveranderlijkheid en voortdurende beweging van deeltjes van vaste stoffen plausibel te maken. Tenslotte wordt gepoogd de aard van een deeltjesmodel te benadrukken door het kader voor deeltjesverklaringen en het al dan niet bestaan van de deeltjes expliciet aandacht te geven.

In hoofdstuk 4 worden de hiervoor genoemde keuzen in detail uitgewerkt. De keuzen voor bepaalde activiteiten en bijbehorende verwachtingen over het te realiseren onderwijsleerproces worden hierin uitgebreid beschreven en verantwoord. Voorafgaand aan de lessenserie dienen leerlingen te hebben geleerd diverse aspecten van het gedrag van materie te beschrijven op macroscopisch niveau. Dit betreft gaswetten, warmtegeleiding en verschillen en overgangen tussen de drie aggregatietoestanden. De lessenserie zelf bestaat uit 23 activiteiten. De gebruikte werkbladen voor leerlingen zijn te vinden in bijlage A. De eerste twee activiteiten hebben tot doel het oproepen van een theoretische oriëntatie met betrekking tot bekend gedrag van gassen. Er wordt geprobeerd om leerlingen te laten zien waarom het zinvol kan zijn om tot beter begrijpen van dat gedrag te komen en welk soort problemen opgelost zouden moeten worden om tot een dergelijk dieper inzicht te komen.
In een later stadium wordt geprobeerd een theoretische oriëntatie op te roepen met betrekking tot bekend gedrag van vaste stoffen en vloeistoffen. Dit gebeurt enerzijds middels uitgebreide aandacht voor een verklaring voor warmtetransport, waarvan leerlingen waarschijnlijk

een bredere toepasbaarheid zullen vermoeden, en anderzijds via de aandacht voor het algemene kader voor deeltjesverklaringen, waarvan verwacht wordt dat deze het modelleerproces van leerlingen zal gaan sturen.
Het model dat na de tweede activiteit wordt geïntroduceerd bestaat uit bewegende en botsende bolletjes en wordt geïllustreerd door een computersimulatie (zie bijlage B). De introductie vindt plaats via een analogie: het gedrag van gassen wordt vergeleken met het gedrag van de bolletjes. Hierdoor blijft het bestaan van de deeltjes in eerste instantie impliciet.
Nadat het model gebruikt is om enkele opgeroepen problemen op te lossen, gaan leerlingen het model verder ontwikkelen. Via het zoeken naar een verklaring voor de wet van Gay-Lussac, stellen leerlingen diverse hypothesen op voor de relatie tussen temperatuur en het model. De verwachting is dat na vergelijking van deze hypothesen gekozen zal worden voor een verbinding tussen temperatuur en de snelheid van de bolletjes. Vervolgens worden leerlingen gestimuleerd om een mechanisme te ontwikkelen waarmee het sneller bewegen van bolletjes bij een hogere temperatuur begrepen kan worden, namelijk via botsingen met snellere deeltjes. Wanneer eenmaal duidelijk is dat het in geval van temperatuurstijging niet nodig is om aan te nemen dat de bolletjes zelf warmer worden, wordt het principe van onveranderlijke deeltjes besproken. Daarnaast worden leerlingen gestimuleerd aannames over lege ruimte en elastisch botsen aan het model toe te voegen opdat de deeltjes inderdaad voortdurend kunnen blijven bewegen. Tenslotte wordt de overstap naar een bredere toepasbaarheid van het model gemaakt. Tijdens het verklaren van bekend gedrag van vaste stoffen en vloeistoffen, worden leerlingen ertoe aangezet om tevens onderlinge krachten in hun model op te nemen. De uiteindelijk door diverse groepen leerlingen ontwikkelde modellen worden in de laatste les met elkaar vergeleken tijdens een soort conferentie.
Tijdens het toepassen van hun model geven leerlingen verklaringen. Via samenvattingen van deze verklaringen wordt geprobeerd om het algemene kader voor deeltjesverklaringen expliciet te maken en leerlingen te stimuleren tot reflectie op de aard van de deeltjes. In het bijzonder wordt aandacht besteed aan de mate van zekerheid over het bestaan van de bolletjes.

In hoofdstuk 5 wordt het daadwerkelijke onderwijsleerproces, zoals dat in de klas heeft plaatsgevonden, beschreven en vergeleken met de verwachtingen die zijn geformuleerd in hoofdstuk 4. Het hoofdstuk besteedt vooral aandacht aan het proces in de tweede ronde, dat wil zeggen aan de hand van het op basis van de eerste ronde verbeterde onderwijsmateriaal. De belangrijkste resultaten zijn de volgende:

- We zijn er niet voldoende in geslaagd om leerlingen op een adequate manier voor te bereiden op de introductie van het model. Het lijkt verstandig en mogelijk om leerlingen een sterker motief voor deze introductie te verschaffen.
- De bedoelde theoretische oriëntatie met betrekking tot een bredere toepasbaarheid van het model werd in redelijke mate bereikt. De uiteindelijke modellen pasten echter niet geheel in het kader voor deeltjesverklaringen. Een verbetering van de voorkennis op het gebied van macroscopisch gedrag van materie en meer nadruk, in de laatste fase van de lessenserie, op de relatie tussen de snelheid van de deeltjes en de temperatuur, lijken noodzakelijk.
- Leerlingen leken het model te accepteren als een bruikbaar middel om verschijnselen van gasdruk te verklaren. Echter, in volgende verklaringen was de rol van botsingen veel minder nadrukkelijk. Om deze situatie te verbeteren zouden voorgaande activiteiten zodanig ingericht moeten worden dat het zoeken naar mechanistische verklaringen een

belangrijker doel wordt voor leerlingen.
- Op bepaalde momenten week het daadwerkelijke modelleerproces van leerlingen af van onze verwachtingen. Om leerlingen te stimuleren de bedoelde relatie te leggen tussen temperatuur en de snelheid van de deeltjes, zouden verklaringen waarin deze relatie een rol speelt explicieter vergeleken moeten worden met verklaringen waarin wordt aangenomen dat de deeltjes zelf warmer of kouder worden. Daarnaast is gevonden dat alle leerlingen de hypothese van lege ruimte tussen de deeltjes accepteerden, maar dat de hypothese van elastische botsingen gaandeweg bij steeds meer leerlingen conceptuele problemen opleverde.
- Tenslotte is gevonden dat de geplande reflectie op gegeven deeltjesverklaringen verbeterd moet worden. De reflectie op het bestaan van de deeltjes verliep min of meer zoals verwacht.

Hoofdstuk 6 beschrijft de evaluatie van de lessenserie door leerlingen en docent. Aan de hand van een open vragenlijst (zie bijlage C) hebben leerlingen in de eerste en tweede ronde hun ervaringen met de methode beschreven. In vergelijking met de eerste ronde leken leerlingen de lessenserie in de tweede ronde meer te waarderen. Ze klaagden minder over te veel herhaling en het model leek al meer relevant beschouwd te worden. Expliciet genoemde positieve aspecten hadden voornamelijk betrekking op hun eigen actieve betrokkenheid bij het verloop van de lessen. Negatieve opmerkingen betroffen de lengte van de klassikale discussies en enkele leerlingen vonden het vervelend dat ze soms te nadrukkelijk in een bepaalde denkrichting geduwd werden. Uit de afsluitende interviews (zie bijlage D), die alleen na de tweede ronde zijn afgenomen, kwam naar voren dat leerlingen over het algemeen vonden dat ze, meer dan in andere lessen, actief betrokken waren bij de lessen. Behalve de reeds genoemde opmerkingen van enkele leerlingen over de mate van sturing, gaven diverse leerlingen aan dat zij de bedoeling van de eerste activiteiten (ter voorbereiding van de introductie van het model) niet goed hadden begrepen. Hoewel het probleemstellende karakter van de lessenserie niet spontaan door leerlingen werd genoemd, hadden zij hier desgevraagd wel waardering voor.
Via interviews met de docent, tijdens en na de eerste en de tweede ronde, is achterhaald welke aspecten van de lessenserie voor hem moeilijk hanteerbaar waren. In de eerste ronde betroffen deze vooral het voorbereiden en uitvoeren van de lessen volgens het vastgestelde scenario. Tevens bleek de voorkennis van de leerlingen niet op alle punten adequaat. In de tweede ronde werd op deze punten verbetering geconstateerd. De docent bleef het echter nog steeds moeilijk vinden om goed te reageren op momenten waarop het proces in de klas te ver van het scenario dreigde af te wijken. In het bijzonder werd het hanteren van klassikale discussies als moeilijk ervaren. Over het geheel genomen was de docent positief over de ontworpen benadering. Hij had de lessen met plezier gegeven en had de indruk gekregen dat de leerlingen het ook leuk hadden gevonden. In het bijzonder was hem opgevallen dat de leerlingen naar omstandigheden zeer gemotiveerd gewerkt hadden.
Vervolgens worden in hoofdstuk 6 de twee onderzoeksvragen uit het eerste hoofdstuk beantwoord. Er wordt geconcludeerd dat we redelijk goed geslaagd zijn in het ontwerpen van een onderwijsleerproces waarin leerlingen de gestelde doelen bereiken. In vergelijking met resultaten uit de literatuur, gepresenteerd in hoofdstuk 2, lijken de leerlingen in onze benadering een model te hebben ontwikkeld waarin de deeltjes minder overeenkomsten vertonen met "kleine brokjes materie" en lijken zij een beter, maar nog steeds niet erg expliciet, beeld te hebben van de aard van deeltjesmodellen. Daarnaast is geconcludeerd

dat de meeste gemaakte inhoudelijke keuzen adequaat lijken te zijn. Verdere verbetering lijkt echter wenselijk en er worden enkele suggesties voor verbeteringen gedaan. Deze betreffen voornamelijk de manier waarop:
- de aanvankelijke theoretische oriëntatie kan worden opgeroepen;
- leerlingen gestimuleerd kunnen worden tot het vaststellen van de relatie tussen temperatuur en de snelheid van de deeltjes;
- het voor leerlingen zinvol kan worden om op het algemene kader voor deeltjesverklaringen en op de onveranderlijkheid van de deeltjes te reflecteren.

Ook de niet-inhoudelijke keuzen die in hoofdstuk 3 verantwoord zijn, lijken na evaluatie van het daadwerkelijke onderwijsleerproces nog steeds adequaat. Met name het probleemstellende idee wordt als waardevol beschouwd, omdat het hierdoor voor leerlingen mogelijk wordt om te begrijpen waarom bepaalde hypothesen gesteld worden en om actief in het modelleerproces betrokken te zijn.
Het probleemstellende karakter van de lessenserie wordt vervolgens beknopt weergegeven middels een structurele beschrijving. Deze structuur, die wellicht breder bruikbaar is, wordt besproken in vergelijking met de structuur van enkele andere bekende benaderingen. Hoofdstuk 6 wordt afgesloten met een reflectie op de algemene kenmerken van probleemstellend onderwijs in het licht van de aanstaande herstructurering van het onderwijs in de bovenbouw van havo/vwo en in het licht van de recente discussie over het imago van de natuurkunde.

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Curriculum vitae

Marjolein Vollebregt werd geboren op 17 juni 1967 te Wageningen. Haar VWO-diploma behaalde zij in 1985 aan het Maurick College te Vught. In mei 1991 studeerde zij af aan de Technische Universiteit Delft in de richting Technische Natuurkunde. Haar afstudeerwerk betrof een vakdidactisch onderzoek naar begripsproblemen van leerlingen met betrekking tot de bouw van materie. Dit onderzoek werd uitgevoerd in het Centrum voor Didactiek van Wiskunde en Natuurwetenschappen te Utrecht. Vervolgens is zij in januari 1992 begonnen aan de Tweede Fase Lerarenopleiding aan de Universiteit Utrecht, waar zij in december van dat jaar haar eerste-graads leraarsbevoegdheid haalde voor het vak natuurkunde.
In maart 1993 is zij bij het Centrum voor Didactiek van Wiskunde en Natuurwetenschappen te Utrecht in dienst getreden als assistent in opleiding. In deze functie heeft zij het onderzoek verricht waarover in dit proefschrift wordt gerapporteerd. Sinds augustus 1998 heeft zij een voorlopige aanstelling als docent natuurkunde aan het Sint Bonifatiuscollege te Utrecht. Daarnaast zal zij, na haar promotie, een voorlopige aanstelling houden bij het Centrum met als opdracht het vertalen van opbrengsten van vakdidactisch onderzoek naar de schoolpraktijk.