Uncommon, unnatural and unknown[1]

B. van Berkel
Sectie Chemiedidactiek, CD-β
Universiteit Utrecht

Summary
In this review article, I will first give a description of the content and structure of M.J. Vollebregt's thesis, titled, "A problem posing approach to teaching an initial particle model". This is followed by my interpretation of the results of her study (explaining the known in terms of the unknown), and a discussion and evaluation of its underlying pedagogical and content-specific choices.

1. Introduction: description of content and structure of the thesis
Vollebregt's thesis (1998) is a pleasure to read. Firstly, it is concisely written using good English, and the structure of the thesis is clearly laid out. Secondly, Vollebregt answers her research questions clearly and in a refreshingly honest and candid way, i.e., critically and scientifically.

Vollebregt reports on a *developmental* research project concerning the design and cyclic trial of a problem posing approach to teaching science[2]. The case study performed concerns a topic which forms a part of the Dutch physics curriculum (HAVO/VWO, 15 and 16 year olds) called by her "the particulate nature of matter" (p.1).
The research questions are stated as follows: (p. 4; italics in original)

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?*

These questions are answered step-by-step by way of a detailed and original *scenario*. Following Lijnse (1995, p. 196), Vollebregt characterises the latter as follows (p. 35):

> 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.

The learning and teaching results achieved by the scenario which has been trialled twice, and the underlying *choices*, are thoroughly evaluated at the end of the thesis (Ch. 6).
The method of developmental research consists of classroom-based, empirical revisions of the designed scenario by taking in account, "to what extent the intended and expected process really takes place and why it does or does not" do so (p. 34). Vollebregt concludes that her scenario, designed

in accordance with these choices, leads to a "reasonable extent" (p. 149) to the realisation of the intended *aims* formulated at the beginning of her thesis (p. 3):

(i) pupils learn that, according to science, matter consists of specific particles;
(ii) pupils learn to use particle models in order to explain and predict several relevant phenomena;
(iii) pupils come to understand the nature of particle models and scientific modelling.

Besides aims, content-specific choices related to the structure of the scenario, Vollebregt distinguishes a third category of choices, called by her "basic ideas" (p. 41). The latter are specifications, for the teaching of an initial particle model, of the *problem posing approach* for which Klaassen (1995) laid the theoretical foundation while developing a scenario for teaching the topic of radioactivity. The "basic ideas" are formulated by her as follows:

* 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.

In brief, the purpose of her study is to develop and trial a scenario, account for the choices made, and evaluate these together with the achieved aims. Let me now elaborate on a number of points relevant for my interpretation of the results of her study (section 2) and for my evaluation of its underlying pedagogical and content-specific choices (section 3).

Vollebregt analyses in chapter 2 of her thesis a number of innovative, mostly constructivistic, attempts in science education to solve the problem of teaching and learning, while aiming for *understanding,* the "particulate nature of matter". Following researchers as P. H. Scott and R. Duit, she distinguishes, two kinds of constructivistic teaching strategies. The first strategy is based on the staging of a cognitive *conflict* and its resolution, while the second is based on developing pupils' ideas consistent with set aims, while reinterpreting pupils' alternative ideas (p. 30). Both constructivist strategies, she argues (following Klaassen, 1995), wrongly presuppose that pupils' ideas are *not* largely correct. Furthermore,

> 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 (p. 161).

Failing this, she argues that both constructivistic strategies do not succeed in solving the problem, producing as a result either misconceptions or confusion with pupils, that is, "some hybrid of parts of their correct knowledge of *tiny bits* combined with taught aspects of scientific particle models" (p. 14). The review of the science education literature for previous, largely failing attempts to improve on the current teaching of particle concepts leave Vollebregt with five sub-problems. These problems (pp. 27-28, 41), for which her scenario tries to give solutions, have to do with the following: finding for pupils a worthwhile aim for the particle model to be learned, deciding on the content of the model and its introduction and subsequent development, and making pupils reflect on the nature of particle models. After concluding that the problem of "teaching an initial particle model", as it says in the title of her thesis, is still a largely unsolved problem, she formulates as a preliminary solution the four "basic ideas".

The scenario is described and discussed in chapter 4, and contains carefully selected and planned activities as well as "*expectations* of the course of the actual process of teaching and learning" (p. 4). It consists of twenty three activities (pp. 45, 46) which intend to teach pupils gradually to use, explicate, and understand a classical particle model while attempting to explain relevant macro-laws and phenomena. After a theoretical orientation that focuses on the *need to explain*, the first two activities deal with relevant macroscopic knowledge. The next two activities (3 & 4) introduce a suitable, simple model which postulates tiny balls in permanent motion while leaving the invariance of these particles *implicit*. A computer simulation called "Gassim" (p. 187) serves as a representation of this model for pupils who learn to apply it, for example giving an explanation of gas pressure in terms of colliding particles (activity 5).

The assumption of the invariance of particles is deemed *crucial* and therefore receives much attention in Vollebregt's thesis and scenario where it is made *explicit* to pupils in activities 6, 7 & 8. In order to explain Gay-Lussac's law, pupils learn to choose one from a number of specific hypotheses which are formulated in terms of "either the temperature, the speed, the mass, or the diameter" (p. 76). In the process of choosing the most plausible candidate (i.e., speed), pupils also learn to assess and formulate arguments which support the assumption of invariant particles. This could lead pupils to pose questions about the mechanism involved here (transfer of momentum) which is dealt with in activities 9, 10, & 11. Whether these particles exist or not is dealt with in activities 13 & 14 on Brownian motion. Another two assumptions made in the classical particle model, empty space and perfectly elastic collisions, are dealt with in activities 15, 16, & 17. In the next series of activities pupils extend or apply the kinetic model to other macroscopic regularities or phenomena concerning liquids and solids, as well as gases. The scenario ends with activities in which pupils compare the models they have arrived at in the classroom with the model scientists like Clausius have arrived at historically. In this way pupils gradually come to learn to explain and predict what they already know from their school physics, namely macroscopic laws on matter, in terms of an unknown and initially strange new theory about *invariant particles and* the latter's mechanical properties and interactions.

In chapter 5, the *actual* process of teaching and learning is described and analysed while "accounting for possible *deviations* of the expected course of events" (p. 4). This relatively long chapter (60 pages) contains a wealth of student-student and teacher-student discussions, very rich data collected in the classroom using three tape recorders. Finally, chapter 6 deals with the evaluation of the problem posing approach – its aims, content specific choices, and basic ideas - Vollebregt has chosen as a basis for the design and trial of her scenario to teach and learn "the particulate nature of matter".

2. Explaining the known in terms of the unknown

I will continue this review article by giving my *interpretation* of what Vollebregt has achieved in her research on a scenario of the teaching and learning of an *initial, classical* particle model. This interpretation was triggered by one of her choices, which came to underlie the scenario as revised after the first trial (p.45), a choice which initially puzzled me.

At the beginning of her thesis Vollebregt states, that "pupils' pre-knowledge is largely correct and *therefore* an adequate and productive *starting point* for further learning" (p. 3). But she decides to use for the second trial another starting point for the scenario, namely *pupils' previous school* knowledge on macroscopic laws, relevant for pupils' attempts at explaining this knowledge in terms of an initial particle model. Thus, although she argues strongly that pupils have a largely correct, naive theory of matter (p. 12), called by her a theory of 'tiny bits' (p. 13), she does *not* use this theory as a starting point for her scenario. She motivates her new choice as follows:

> ... starting from a model of tiny bits does *not* appear to be the best option, for the analysis [in Ch. 2] 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 (p. 27).

Subsequently, pupils learn to apply this model to macroscopic laws, i.e., gas laws. At several other places in the scenario similar measures are taken to prevent or "discourage" (p. 76) or "minimise these kind of associations" (pp. 55, 93) with pupils' naive theory of matter. The strategy here is to "*postpone* questions concerning the ongoing movement of the balls, which indeed are better raised at a later stage" (p. 155).

Knowledge of pupils' theory of tiny bits is used by Vollebregt in two other ways. Firstly, as noted above, to avoid premature and unproductive associations with pupils' naive theory of matter. For example, the electrical device demonstrating tiny balls in motion led pupils in the first trialled scenario to make unintended and unwanted connections with "the cause of the ongoing movement of the particles of the model" (p. 92). This demonstration or *analogy* was therefore replaced in the second trial by a computer *simulation* demonstrating permanent or intrinsic motion. Vollebregt remarks that "this time not one pupil expresses doubts" (p. 92) on the cause of the ongoing movement. Secondly, knowledge of pupils' naive theory of matter is used for staging "at appropriate stages during the process of conceptual development" (p. 157), a productive confrontation between pupils who do and pupils' who do not attribute the macroscopic property temperature to 'tiny balls'. Thus, *conceptual interference* of pupils' intuitive theory of matter with the aims of the scenario, learning about scientific particles and modelling, is either avoided or used selectively.

Vollebregt chooses as the starting point of her scenario pupils' previous *school* knowledge on macroscopic regularities (e.g. gas laws) relevant to the explanatory power of the theory of scientific particles they are about to learn. Further, she appeals throughout her scenario to pupils' intuitive need to explain at a deeper level these kind of regularities or laws, "more specifically, on giving explanations in terms of the behaviour of *constituting* elements, which differ from the behaviour of the system as a whole" (p. 153). Also, Vollebregt does not use at the beginning of her scenario the usual constructivists' strategy to make pupils' ideas, preconceptions, or naive theories *explicit* in order to stage a *conflict* between their common sense ideas and the *scientific* particle ideas of physics to be learnt[3]. Vollebregt's scenario starts, on the other hand, with pupils' previous *school* knowledge on macroscopic laws in order to *extend* this knowledge in the direction of scientific particle models.

In the first design, she uses an *analogy* to demonstrate an initial particle model. But in the second design she decides to use a computer *simulation* which, after a theoretical orientation, introduces pupils quite effectively, it seems, into the micro-world of what she calls "tiny balls". I think that there is a small, but important difference in meaning between an analogy and a simulation. In the case of an analogy the focus is on a comparison of a situation or a process with what is already familiar or known. In the case of a simulation, however, there is a strong emphasis on the unfamiliar or unknown aspects which are taken as extrapolated or idealized from a familiar or known situation. For example, in the simulation of space travel astronauts come to experience unknown flight conditions for themselves. Likewise, pupils in Vollebregt's scenario come to experience and/or learn about for themselves unknown conditions which apply to "tiny balls".

This unknown world is quite different from the macroscopic world of "tiny bits", that is, tiny bits of matter which upon division retain *all* the properties of macroscopic substances like colour, smell, temperature, etc. Pupils then learn in Vollebregt's scenario what she calls a "simple" (p. 38), but, nevertheless for pupils, an initially strange model. They learn to *explain* and *predict*, in terms of this model, more macroscopic phenomena, especially many macroscopic *regularities*, such as the gas laws, phases of matter, and heat flow.

As she later puts it, looking back at the cyclic developmental research process of the scenario, the kinetic particle model is introduced initially to the pupils in an *instrumentalistic* way (p. 73). And subsequent teaching activities are designed in order to furnish pupils with a variety of experiments and arguments to help them understand that it is not only intelligible and plausible, but also *fruitful* to explain previously known macroscopic phenomena in terms of the "unknown" but *real* micro-world[4]. Thus, this micro-world is initially and at least partly unknown to pupils, and when they start to learn it, it is likely to be perceived as "strange" (p. 55). Ideally, at the end of the teaching-learning process as instigated by the scenario, pupils come to learn and to accept as "realistic" (p. 73) on empirical and/or logical grounds the following *counter-intuitive* claims, that is, claims which differ from their initial intuitive beliefs and go against their daily life experience.

i) Scientific particles are not really particles ("tiny bits"), since they show only some of the macroscopic properties of gross matter [i.e. large amounts of particles], namely the mechanical and geometrical properties mass, volume, speed, and time. As Vollebregt emphasizes at various places in her thesis, the particles are *invariant* with regard to volume and mass, therefore quite unlike "tiny bits", an assumption which might initially strike pupils as "far-fetched" (p. 72).
ii) Scientific particles undergo permanent intrinsic motion; in daily life we always have to push or pull things to get them to move, "the next strange assumption" (p. 116).
iii) Scientific particles move in a void, whereas in daily life we experience that everything is full of some substance or of some matter, another "strange" (p. 115) hypothesis.
iv) *Scientific particles perform*, if they make contact with each other or other kinds of particles, perfect elastic collisions, another "strange" (p. 115) hypothesis.

Besides assumptions or hypotheses about micro-particles and their properties *constituting* the micro-world (i, ii, & iii), pupils have to learn two other *kinds* of hypotheses involved in the classical kinetic particle model. The latter two kinds of hypotheses are clearly distinguished and explicitly addressed by Vollebregt in her scenario and in the general framework of particle explanations pupils must learn to use (p. 37, Figure 3.1).

Firstly, she mentions hypotheses on the *interactions* between the posited particles, which can be perfect collisions (hypothesis iv) or mutual attractions by way of (particle specific) forces. Secondly, she mentions hypotheses stating the relationships between the *micro-world*, its constituents and the laws describing their behaviour, and the *macro-world,* its phenomena and macroscopic laws; for example, the relation between the kinetic energy (speed) of the particles and temperature, and the relation between the mass/volume of a particle and the mass/volume of a body constituted by these particles.

Judging from their group discussions, pupils experience some conceptual difficulties with the implications of the first category of hypotheses (i-iii), that is, the ones about the *existence* of these particles and their limited set of geometric and mechanical properties. Since these hypotheses describe the constituents of the micro-world, I will call these *constitutional* hypotheses. Problems with these *constitutional* hypotheses show up in some places in the student-student and teacher-student discussions. For example, a number of pupils still think at the end of intensive group work and discussion that "tiny balls" have a temperature, thereby attributing a non-mechanical macroscopical property to a microscopical entity. A reason for this incorrect attribution might be that these *constitutional* hypotheses are not explicitly introduced or treated as a separate category in the scenario. These hypotheses do not form a *visible* part of the general framework of particle explanations (Figure 3.1, p. 37) which pupils must learn to use and, ideally, to reflect upon. However, they are presupposed, both by the hypotheses on *interactions* and by the hypotheses on micro-macro relationships.

Similarly, more explicit attention is probably needed to address the fact that the scientific particle explanations of macroscopic phenomena involve only a quite limited set of mechanical variables (De Vos, 1996). The activities (6, 7, & 8), where pupils try to explain the rise in pressure of a gas when the temperature is raised (Guy-Lussac's Law), are most successful in this respect. Pupils frame and/or are offered for this purpose four hypotheses: (a) in terms of a possible increase in mass; (b) in terms of a possible increase in volume; (c) in terms of an increase in tempe-rature of tiny balls; (d) in terms of increasing speed. The student-student and teacher-student discussions related to these and ensuing activities make fascinating reading (pp. 98 - 114). Pupils struggle in groups with these conflicting hypotheses trying to find pro and con arguments for their position. In the end, the pupils dismiss the first two hypotheses, with some opting for temperature of particles (c) and some for speed (d). So in this activity pupils do learn to work with a small set of mechanical variables, as presupposed by the classical particle model, but it seems that as yet they have not been made fully aware of the limited number of mechanical variables involved. At this point in the scenario it would be worthwhile, I think, to try to make more explicit to pupils what *the point* is of selecting just this set of mechanical variables.

In a later activity on Brownian motion, pupils also learn that the strange invariant particles can have a *visible* effect, namely on tiny bits of ash. At this stage the kinetic model is shown to be not only fruitful in explaining and predicting phenomena, but the entities and properties it uses to do so are now gradually taken as *real* by pupils, which adds considerably to the acceptability of the kinetic particle model. In this way, the unknown micro-world not only becomes known to the pupils, it also becomes less strange and understood thereby.

3. Discussion and evaluation

In chapter 6, Vollebregt evaluates and reflects on the choices underlying the designed scenario, that is, on the aims, content-specific choices and basic ideas (pp. 152, 158).

As I have argued elsewhere (Van Berkel, 1999), it is possible to gather valuable information on a designed curriculum unit or scenario by performing, consecutively:

- a *consistency analysis* in order to see whether and to what extent the intended design criteria (or choices) are realised consistently in the designed unit (or scenario);
- a *reversed design analysis*, that is, inferring from the actually realised content of the unit or scenario (contexts, concepts and activities) any *tacitly* used design criteria, which might have led to unintended, unforeseen or even, perhaps, to unwanted consequences;

- a *redesigned proposal* for the topic or theme of the unit or scenario in the light of the performed consistency analysis and a reversed design analysis.

Put in these terms, Vollebregt performs (Chapter 6) an admirably clear and consistent analysis of two subsets of her design criteria or *choices*, underlying the designed and trialled scenario, namely the aims and the (other) content specific choices (p. 152). She further gives a number of useful recommendations for redesigning the scenario, but she is relatively silent, as I will argue, on the implications of her actual designed scenario on some of her initial choices of basic ideas.

As for the aims, she modestly concludes that "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" (p. 152). A careful reading of the evidence presented in her thesis will amply confirm this conclusion. Further, Vollebregt frankly admits that the third aim, that is, "pupils come to understand the nature of particle models and scientific reasoning" (p. 3) has, for the pupils "hardly resulted in general knowledge about the nature of particle models" (p. 151). As she puts it:

> ... 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 (p. 151)

At the end of her evaluation of the aims set by the scenario, she concludes "that such a general aim is probably too far to reach within just one sequence, dealing with just one particle model"

It is to be hoped, as well as expected, I think, that a carefully planned and trialled follow-up scenario developed along problem posing lines will succeed in reaching this valuable aim. This seems to me all the more important, since I would argue that it is especially this *general* aim which is most worthwhile and meaningful for the *cultural* and *societal* preparation of *all* pupils, that is, "for becoming responsible citizens" (p. 1); whereas the realisation "to a reasonable extent" (p. 149) of the first two aims mentioned above, is, I think most relevant for those students who prepare themselves for further study in science or physics (pp. 1, 40).

With regard to the other content-specific choices related to the introduction and further development of the scenario, Vollebregt concludes that most "seem to be adequate" (p. 158). She gives many suggestions for improvement of the scenario. First of all, the initial theoretical orientation could be focused more on pupils' *need* for deeper explanations by exploiting "the differences between the properties of a *system* and its *constituting* elements" (p. 153) and the special status of "law-like" statements. Secondly, her suggestions concern the way in which "pupils may arrive at the correspondence between the temperature of a gas and the speed of the particles" p. 158), for example, by providing knowledge on perfect collisions previous to the actual teaching of the new topic on scientific particles. Thirdly, her suggestions concern the way in which "it may become worthwhile to pupils to reflect on the general framework and the invariant nature of the particles" (see also my remarks above on *constitutional* hypotheses and the limited set of mechanical variables used in the classical particle model).

I would like to suggest at this point that a number of *postponed* conflicts (such as the one staged in activities 6, 7, & 8 where pupils either do or do not attribute the macroscopic property temperature to scientific micro-particles) could prepare pupils for a productive confrontation of their newly learned scientific theory of tiny balls and their intuitively held theory of tiny bits made explicit in the process. As with setting the general aim, "understanding the nature of particle models and scientific reasoning" discussed above, such a newly set, general aim would require one or more carefully planned and trialled problem posing scenario's.

What pupils appear to need, judging from the empirical evidence given in Vollebregt's study, is, firstly, to be provided with at least some core elements of an *alternative* theory to their intuitive theory of matter. Secondly, they need ample experience in using the newly provided theory, that is, for explaining and predicting macroscopic phenomena. At inter-mediate and later stages in the scenario the pupils might also become aware of what exactly their initial, naive theory of matter consisted; that is, how the assumptions of the latter differ from the assumptions about constituents and interactions entailed by the newly learned scientific theory. Thus, the strategy of staging a number of postponed conflicts could lead in the end to a *productive confrontation of frameworks*. After all, only after these preparations are pupils in a position, i.e. have means and motives, to compare the new framework of the mechanical, kinetic model with their initial intuitive framework of tiny bits.

Finally, Vollebregt concludes that the basic ideas "also still seem adequate for the topic of particle models" (p. 158). Looking back from the actual details and justification of the scenario, I disagree to a certain extent here, at least with regard to the first two basic ideas mentioned above. On the basis of the interpretation given in the previous section (*explain the known in terms of the unknown*) I think that almost the reverse is true of what is stated in the first basic idea: "Pupils should be actively involved in *the integration of new information into what they already know*". Instead, pupils are, according to me, actively involved in the learning process instigated by the scenario, while attempting to explain what they already know in terms of a very special kind of "new information", namely, in terms of an initially, partly implicit, classical particle model.

Further, as I have stressed, the actual starting point of the scenario consists in pupils' previous *school* knowledge about relevant macroscopic knowledge. It does *not* consist in pupils' previous pre-educational knowledge as seems to be implied, and is so stated by Vollebregt (p.3), in the second basic idea. Reading Klaassen (1995, pp. 9 - 20), I expected that pupils' pre-educational knowledge would be used as the natural starting point, especially after he argued at length that pupils' knowledge is largely correct. As argued above, I think that pupils' pre-educational knowledge has been used in the design of the scenario in a different way, namely to design points of *productive interference* between the set aims of the scenario and pupils' knowledge. As Vollebregt puts it, "Instead, specific *expected* difficulties, such as the implicit connection between the temperature of the particles and the temperature of the macroscopic amount of gas were dealt with at appropriate stages during the process of conceptual development" (p. 157).

Looking back from the actual details of the scenario to the initial basic ideas seems to lead to a revision of the first two of those ideas. The first basic idea could be reformulated as follows:

Pupils should be actively involved in learning to explain and predict in a *deductive way* what they already know, that is their relevant macroscopic knowledge, in terms of an initially unknown, and partly implicit scientific particle model.

A scenario based on this reformulated basic idea – as I think Vollebregt's scenario is in fact – implies that pupils' do extend their previous school knowledge, but in a rather special way, namely, by using hypothetical-deductive reasoning. This kind of reasoning differs, especially when it concerns scientific particles, from the way pupils extend their previous knowledge of a topic located strictly within the macroscopic domain where forms of inductive reasoning, such as generalizations, play a primary part (Klaassen, 1995). The second basic idea could be reformulated as follows:

Pupils' pre-educational knowledge about specific topics, assumed to be largely correct or hardly developed, is to be used at appropriate points in the scenario in order to ensure *productive conceptual interference.*

Depending on the aims set for the scenario, and the content-specific requirements, the *starting* point could consist in either pupils' previous school knowledge or in pupils' previous pre-educational knowledge. Thus, I have argued here that the actual course of the process of teaching and learning "the particulate nature of matter" *empirically supports* a hypothetical-deductive way of extending pupils' school knowledge, as well as a design principle which aims at the productive interference of set aims and pupils' pre-educational knowledge.

Finally, the question can be raised to what extent the pupils are provided with a problem posing approach, to what extent with an explicit teaching approach, and to what extent with an implicit teaching approach. For example, with regard to the assumption of invariance, the scenario starts with an *implicit* teaching approach which prepares pupils for an *explicit* and/or *problem posing* approach later on in the scenario (Vollebergt, 1988, pp. 47, 86, 164). As the results of the case-study amply show, the com-bination and order of teaching approaches actually chosen in the scenario appear to enable pupils to see the point of what they are doing, that is, to engage meaningfully in the modelling process with regard to specific particle explanations. As already noted, further attempts to revise the scenario in ways which are more problem posing and/or explicit are announced at various places in the thesis.

It is probably neither possible nor desirable for all pupils to learn all the time by trying to pose problems raised by a particular scientific topic or theme. Vollebregt's research, though, has convincingly and empirically shown that most pupils learn to appreciate most of the carefully *selected* questions and *provided* problems with regard to "the particulate nature of matter" (p.1) as important and interesting *for* them, and that they can solve these problems with real understanding. Thus, although initially the scientific particles are perceived by pupils as uncommon, unnatural and unknown, in the end they are not unappreciated.

Notes

1. I apologise that this review article is written in English. Both Vollebregt's and my own thesis are written in this language, so I started out to write my drafts in English, too. Later on I decided to stick to it for reasons of time and efficiency.
2. Italics are mine, unless otherwise indicated; page numbers in parentheses refer to Vollebregt (1998).
3. The latter, scientific ideas are aptly called *uncommon* sense by Cromer (1993). In a book on a similar theme, Wolpert (1992) refers to the *unnatural* nature of science.
4. Popper (1963, p. 63) introduces the idea of explanation or "reduction of the known to the unknown" to capture what goes on at the research front (or here at the learning front). It is only *after* new knowledge has been acquired, that we – scientists and students alike – can apply the 'received' knowledge to other cases, that is, explain *specific* phenomena or regularities in terms of the now acquired *general* theory. Before that, all we can do is to attempt to find an explanation of the known in terms of an *unknown* theory, using in particular "the idea of explaining the visible world by a postulated invisible world" (*ibid.*, p. 89). The scenario helps pupils by providing an initial, partly implicit, model of this invisible world.

Acknowledgement

I want to thank Mary Beth Key for the editing of this review article, and Marjolein Vollebregt and Kees Klaassen for critical discussions on an earlier draft, which enlightened me on some initial factual and interpretive misunderstandings on my part.

References

Berkel, B. van (1999). *The nature and structure of school chemistry*. Utrecht: CD-β Press.

Cromer, A. (1993). *Uncommon Sense*. New York: Oxford University Press.

Klaassen, C. W. J. M. (1995). *A problem-posing approach to teaching the topic of radioactivity*. Utrecht: CD-β Press.

Lijnse, P. L. (1995). 'Developmental research' as a way to an empirically based 'didactical structure' of science. *Science Education, 79*, 189-199.

Popper, K. R. (1965). *Conjectures and Refutations*. New York: Harper & Row.

Vollebregt, M. J. (1998). *A problem posing approach to teaching an initial particle model*. Utrecht: CD-β Press, pp.201 (ISBN 90-73346-38-X).

Vos, W. de & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 6*, 657-664.

Wolpert, L. (1992). *The unnatural nature of science*. London: Faber & Faber.