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ABSTRACT

In the past decade, research on students' ideas has drawn attention to underestimated problems of learning physics. This also particularly applies to Science/Technology/Society teaching. Proposed solutions are mainly inspired by a constructivist cognitive science perspective and are formulated as general teaching strategies that aim at a process of 'conceptual change'--so far with understandably limited success. Developmental research is needed in which small scale curriculum development is cyclically coupled to in-depth classroom research of the social teaching-learning process. It should be based on a communication perspective on teaching and on learning physics as building on and extending common sense. Such research should result in worked out examples of ways of teaching according to new conceptual curriculum structures. Designing such didactical structures constitutes a longer term research program, in which progress is possible. The work of the researchers on the topic of radioactivity is described. Contains 30 references. (Author/PR)

DEVELOPMENTAL RESEARCH AS A WAY TO AN EMPIRICALLY BASED 'DIDACTICAL' STRUCTURE OF PHYSICS: THE CASE OF RADIOACTIVITY

by

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DEVELOPMENTAL RESEARCH AS A WAY TO AN EMPIRICALLY BASED 'DIDACTICAL' STRUCTURE OF PHYSICS: THE CASE OF RADIOACTIVITY

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1. SUMMARY

In the past decade, research on students' ideas has drawn attention to underestimated problems of learning physics. This also particularly applies to STS-teaching. Proposed solutions are mainly inspired by a constructivist cognitive science perspective and are formulated as general teaching strategies that aim at a, more or less forced, process of 'conceptual change'. However, sofar only with understandably limited success.
In our view, 'developmental research' is needed in which small scale curriculum development is cyclically coupled to in-depth classroom research of social teaching-learning processes. It should be based on a communication perspective on teaching and on learning physics as building on and extending 'common sense'. Such research should result in worked out examples of ways of teaching according to new conceptual curriculum structures. Designing such 'didactical' structures constitutes a longer term research programme, in which progress is possible. Our work on the topic of radioactivity is described as an example.

2. INTRODUCTION

Since the fifties, extensive work has been done on improving physics education. A large number of curriculum development projects have tried to do so from several different perspectives. Emphasis has been on teaching 'the structure of the discipline'; on 'being a scientist for the day' and 'discovery learning'; on Piagetian theory and stages of cognitive development; and most recently on so-called science-technology-society education (Yager, 1992). Nevertheless one may seriously doubt whether all these efforts have resulted in real progress, as far as insightful learning of physics is concerned.
In the Netherlands, the PLON-project has made quite an effort in developing STS curricula at the secondary level; its rationale can be briefly characterized as 'teaching physics actively in relevant contexts'. From such teaching, it is expected, on the one hand, that students will experience the content taught as more relevant. On the other, that they will be better able to understand and connect the concepts learned to their out-of-school world.
However, in the last decade, studies on teaching and learning have emphasized the importance of what has become known as 'alternative frameworks' that students bring to the classroom. From this research, it is argued that learning asks for a process of conceptual change instead of conceptual transmission. This may explain that past curriculum efforts have been only moderately succesfull. And thus that we still need to find better ways of teaching science. This paper will deal with our efforts in this direction, in which we try to merge the STS and conceptual change approaches, based on a reconsideration of what 'conceptual change' could mean.

3. FIRST EXPERIENCES WITH TEACHING ABOUT IONIZING RADIATION

Teaching about ionizing radiation and radioactivity in the context of risk and risk perception is a prototypical example of STS teaching. Our experience with a unit on 'Ionizing Radiation' (PLON, 1984; Eijkelhof, 1986) for senior-highschool (higher ability) students, however, did not agree with the above expectations. A summative evaluation showed that though students valued the topic relatively well (particularly girls), cognitive learning results were disappointing, because:

1. In general, students were not inclined to use taught knowledge in their reasoning about situations for which they already had an opinion, such as: disposal of nuclear waste, nuclear energy, having an X-ray.
So, using learned knowledge of physics in life-world situations is not at all self-evident. It seems to ask for a transfer step that is usually not made if students have already a familiar and satisfactory common-sense explanation available.

2. A questionnaire on lay-ideas about 'radioactive radiation' showed that the experimental (plon-)group did not answer much different from students who had been taught traditionally about 'nuclear physics'(Eijkelhof, 1990). This is illustrated by the following typical items:

percentage of students that agree	plon	non-plon
* x-rays remain for hours in the air in an x-ray department	41%	24%
* radiation might be stored in food	52	60
* patients who are irradiated are hazardous to others	19	20

To understand these results we studied students' pre-instructional reasoning about radioactivity by means of interviews (age 16, middle and higher ability). Their ideas about the following contexts were investigated: having an X-ray, irradiation of cancer, nuclear bombs, nuclear reactors, irradiation of food, radioactive waste and background radiation (Eijkelhof, 1990). Apart from many apparent 'misconceptions' and idiosyncratic ideas, in general we could conclude that, from a physicist's point of view, students:

* used an undifferentiated concept of 'radioactive substance/radiation/radioactivity';
* could not differentiate between contamination and irradiation, which is essential for risk perception;
* had a strong association with 'danger', using a 'digital' norm concept.

A newspaper analysis concerning the reports about the Chernobyl-accident showed these ideas also to be frequently present in news media reports (Eijkelhof & Millar, 1988; Lijnse et al., 1990). This may explain their presence in students' reasoning, and the fact that if teaching does not deal with them properly, they will not be 'changed'.

4. 'TOP-DOWN' INSTRUCTION

Before focussing on how to deal with those 'misconceptions', it is first useful to reflect on the teaching strategy used in the unit under consideration.
In general one could say that in a traditional 'structure-of-discipline' type of curriculum, the concepts to be taught are the basic concepts of physics. The sequence in which they are taught reflects its basic 'logical' structure. The situations in which these concepts are to be used are the usual idealized situations. It is precisely this latter aspect that STS-curricula want to change, by teaching in real life contexts, leaving, however, the conceptual stucture and sequencing essentially unchanged. Apart from the fact that, because of the complexity of real situations, some new concepts may have to be added (see e.g. De Jong et al.,1990).

We characterise such a teaching strategy as 'top-down', i.e. both in traditional and in most STS-curricula teaching starts from and focusses on the perspective of physics; teaching it without really taking into account what students already know and think (see below). Thus it is aimed at a direct 'top-down' transmission of concepts, even though the way in which that is done, may include lots of open discussion and discovery activities. In both types of curricula, such teaching unavoidably results in a process of 'forced' concept development, which explains the apparent lack of differences in cognitive learning outcomes shown above.
However, as already mentioned, research has shown that students' alternative frameworks have to be taken into account, asking for, as it is argued, conceptual change instead of conceptual transmission. In STS-teaching, common sense ideas play an even more unavoidable role than in traditional teaching. Students not only appear to have common sense ideas related to the concepts to be taught, that can certainly not be avoided while talking about real life contexts from which they stem, but also related to these contexts themselves. It is this latter type of pre-knowledge that explains why, even if we would succeed reasonably in teaching correct conceptual knowledge, it may still not be used in real life situations, as we have described.

5. CONCEPTUAL CHANGE AS IMPROVED TOP-DOWN TEACHING ?

Thus it was concluded that we should try to find a way to improve our teaching strategy, by taking into account students' pre-knowledge. This reflects our adoption of a 'constructivist' perspective, which means that we agree with statements like 'meaning is constructed' and 'concepts cannot be transferred from teachers to students'(Duit, Goldberg & Niedderer, 1992), etc.. As such, this is an important non-trivial change of perspective, as will be clear from the above. However, on the other hand, adopting a 'constructivist' perspective does not say yet very much about how to teach. The phrase 'the teacher must have a good idea of what concepts the students might already have and then engage students in activities that would help them construct the desired understanding' (Duit,e.a, 1992), may easily be insufficiently interpreted, as we will argue now.
Freudenthal (1991), in a comment on 'constructivism', writes as follows: "If 'constructivism' is to mean anything didactical, it must indicate the one who is expected to 'construct'. (...) If I were to accept the term 'constructivism', I would mean a programme having a philosophy that grants learners the freedom of their own activity."
This points, in our opinion, to a basic problem. When this freedom of learners is ignored, teaching unavoidably results in 'forced' concept development and thus in misconceptions. It is a contradiction to adopt 'constructivism', i.e. the view that students construct their own meaning based on what they already know, and at the same time either to prescribe what they have to construct or to immediately devaluate what has been constructed. The basic problem for constructivist teaching thus is how to design teaching such that it guides students to CONSTRUCT IN FREEDOM the very ideas that one wants to teach. Freudenthal calls this learning process 'guided reinvention' (not to be mistaken for 'classical' discovery learning). In most 'constructivist models of teaching' sofar worked out, it is precisely this necessary freedom of learners to make and follow their own constructions that is either lacking or being underestimated. In fact, one could then cast reasonable doubt on whether such approaches should be called 'constructivist' at all. For instance, in the status-changing-model of conceptual change (Posner et al. ,1982), students' conceptions are essentially considered as wrong ideas that have to be changed as quickly as possible. To do so, the teacher should design activities that lower the status of students' ideas and raise the status of taught ideas. It is hard to see how such an approach may build positively on students' own constructions. This also applies, to a lesser or larger extent, to conflict-strategies (Nussbaum & Novick, 1982) or to the CLISP-approach as described by Driver and Oldham

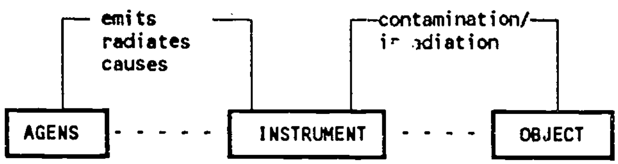
other. Studies of an individual's conceptual development (Scott, 1992; Niedderer and Goldberg, 1993) misses this essential focus of what teaching and learning physics is all about. E.g., this essential interconnectedness of teaching and learning seems precisely to be absent in the following quote: "Once we begin to better understand how children's ideas are likely to progress in particular science domains, then we shall be better placed to develop teaching approaches to support that progression" (Scott, 1992). Such focus on what "is in the mind" (Niedderer and Goldberg, 1993) seems to have its origin in Cognitive Science Research. However, as will be clear from the above, in our view, science education research should take a different route.

7. WAYS OF SPEAKING ABOUT RADIOACTIVE SITUATIONS

In thinking about how to design bottom-up teaching about radioactivity, it is useful first to map out different ways of talking about the topic. That helps to clarify where to start from and in which direction possible teaching activities should contribute to changes of meanings and intentions.

A COMMON SENSE NETWORK OF RELATIONS

What then could this basic pattern of common sense thinking, to start from, be all about? Interpreting the available data, as much as possible from their point of view, we found the following common core in students' life-world reasoning about radioacte events and situations.



nuclear power plants	*radiation*	people (us)
Chernobyl	wind, rain	vegetables
nuclear bombs		walls, air
'machines'		food
waste		

NB: the term *radiation* is not the physicist's term radiation!

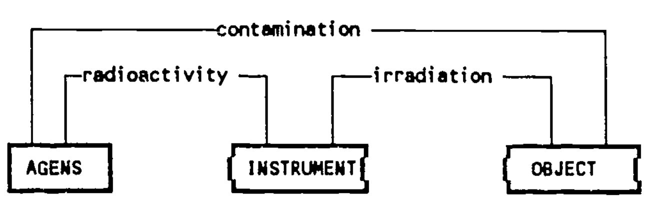
Some common sense relations are as follows:

The stronger the agens the more *radiation* it emits.
Normally an agens is sufficiently protected.
If *radiation* escapes, it may come on or into us.
That can be directly, or by means of wind and rain.
If it comes on, around or in us, it is dangerous.
The more *radiation* the more damage.
The stronger the agens, the larger its effects
The further away from the agens, the less dangerous.
Etc.

This pattern of reasoning is a concrete example of Anderson's (1986) 'EXPERIENTIAL GESTALT OF CAUSATION'. It expresses a general common sense way of causal reasoning. 'Agents' act on 'objects', directly or by means of 'instruments', in which they may have to overcome a 'resistance'. As said above, insightful learning of physics does not ask for 'erasing' this way of reasoning, as it expresses (by definition) everybodies common sense, but for building on and extending it. Though meanings, intentions and ways of talking may have to be changed, the underlying experiential belief system is essentially correct.

A QUALITATIVE MACROSCOPIC NETWORK OF RELATIONS

This network gives the physicist's phenomenological language that describes 'scientific' experiences with ionising radiation.



source	medium	receiver
radioactive-substance	radiation	absorption

The following examples give some relations:
Radioactive substances are at many places.
A radioactive substance emits radiation.

(1986). So we do not agree with Scott et al. (1992) when they say: "Each of these routes attempts to make links between students' thinking and the science view and might therefore be considered to be equally valid constructivist teaching approaches". It is precisely the way in which that link is being developed that makes a crucial difference. Otherwise, the term 'constructivist' becomes almost meaningless.
Of course, this is not to say that such approaches may not improve the learning results as compared to those of traditional teaching. It does explain however that the scope of such improvements is and will remain limited. Basically, these approaches could be characterized as using new strategies to improve top-down teaching. The disciplinary conceptual structure to be taught is still the direct starting point for instructional design. Only the strategies to teach this structure need to be more efficient.

In our opinion, a more radical change seems to be needed. If we want students to really understand what they are learning, we should engage with them in a 'bottom-up' learning process. In analogy to Freudenthal, we could say that we should not teach the concepts of physics (as a product), not even in an above mentioned constructivist way, but guide students in the activity of 'physicalising' their world. Insightful learning can only start where students are, which asks for understanding the concepts and language they use. Activities should be carefully designed such that students can build positively on and extend what they already know. Their own constructions should guide the teacher in this process, that should be driven as much as possible by their own questions and motivations. It should result in a gradual non-forced process of concept development, the endpoint of which cannot be settled in advance, by definition. Thus, teaching objectives can no longer be derived solely on the basis of a logical analysis of the subject domain (Scott, 1992). The design of such teaching is necessarily an empirical proces of closely interconnected research and development, that we therefore call 'developmental research'. It cannot result in general teaching strategies, nor can it start from them. Research on cognitive science is, precisely because of its general scope, of little practical value. On the contrary, we aim at a detailed description and justification of content-specific teaching and learning activities and of the processes to which they may lead. We would call such a result a 'didactical structure' for the topic under consideration. Thus, long term empirical research may eventually lead to a didactical structure of physics, describing both at a theoretical and practical level, which interpretation of the concepts of physics can be meaningfully taught in what way to what level to which students.

6. INSIGHTFUL PHYSICS LEARNING IN A BOTTOM-UP COMMUNICATION PROCESS

These considerations have not come out of the blue, but have grown gradually from a number of experiences in trying to improve top-down teaching from a 'constructivist' perspective (Van Genderen, 1989); Eijkelhof, 1990; Van der Valk, 1992). Even though a recent follow-up study on radioactivity, using a new teaching unit with a number of 'constructivist' activities, has been reasonably successful (Eijkelhof, Van der Valk & Lijnse, 1992b) we concluded that in general a radically different approach may be necessary.
In a case study, again on radioactivity, this approach is being developed now. The study focusses on lower/middle ability students of age 15, who, because of the implementation of STS-ideas in our school system, have now to learn about radioactivity. Our work in this context will now be described as an example of our search for a didactical structure.

We therefore first reconsidered and studied those students' pre-instructional ideas about particles and radioactivity more deeply. The above conclusion that, from a physicists point of view, students have many misconceptions and idiosyncratic ideas, and reason inconsistently across contexts, though both common interpretations in the 'conceptual change' literature, was now considered to be inadequate. In fact, such an interpretation does not reflect what students ARE saying, but only what they are NOT saying, i.e. correct physics. To be able to build on students' knowledge, we should first know what they really mean when they say what they say. If we do not assume that students talk sense and argue rationally and coherently (or at least largely so), then we are in great danger of misinterpreting they are doing or talking about. The only way to avoid this risk is to interpret them as consistent and look for a common and understandable pattern in as much utterances as we have from them (this is completely the opposite of what happens in most questionnaire research on 'misconceptions'). Realising that their common sense belief system about the world, being the system it is, cannot be but largely correct, it ensures that there is a common basis from which understandable communication and teaching can start. Interpreting physics learning as learning to speak in a partly new way about the common world we live in, it can only be learned meaningfully if we engage in a gradual and essentially social process in which mutual understanding is constantly secured. As Freudenthal puts it, as extended and organised common sense. It means that the seeming discontinuity between scientific knowledge and reasoning and common sense knowledge and reasoning (Reif and Larkin, 1991) should be considered as differences between endpoints on a scale. It does not mean that the connection cannot be made 'continuously'. So, if the teacher speaks in the language of physics, even though expressing it in the most simple terms, he cannot be understood as he intends by students who don't know that language yet (see, e.g., Lijnse, 1992). This is the very characteristic of what we described above as top-down teaching. The result is known as verbalism, misconceptions and insufficiently applicable knowledge.
Coming to understand each other is essentially a social process. A process of talking about, interpreting each other's talk about and bringing about events, in which, if necessary, the participants may come to agree on using new conventions. The study of learning physics should thus focus on this social process. How to regulate it, sothat it is rooted in and maintains mutual understanding. Understanding such communication is therefore the key to understand teaching and learning. It means studying learning processes of both students and teachers in relation to each

When irradiated the receiver absorbs radiation, which may cause effects.
Because of that the receiver will not emit radiation.
A radioactive substance can be moved and come on or in the receiver.
A contaminated receiver emits radiation.
Both a source and an object can be shielded.
Etc.

This network can be extended to a quantitative macroscopic network of relations, by means of, a.o., the following concepts:

'strength' of an amount of radioactive substance (as measured by a counter);
kinds of radiation, to be distinguished by means of penetrative power;
decrease of strength (activity) in time (half-life); etc.

A SUB-MICROSCOPIC NETWORK OF RELATIONS

Still another way of talking is in terms of a sub-atomic microlevel. At that level, the descriptions of how things happen at the macrolevel, are 'explained' in terms of relations that, in a certain sense, may be said to describe 'why'.

AGENS	INSTRUMENT	OBJECT
source	medium	receiver
isotopes	α,β,Γ,x-rays	molecules
instable nuclei	He-ions	cells
excited atoms	electrons	ionisation

Some relations:
Activity (or strength) is the number of nuclei that decay per second.
Radiation consists of α, β, Γ, x-rays.
α-radiation consists of He-ions.
When an α-particle 'hits' a receiver it may cause ionisation.
Receivers consist of cells and/or molecules.
Etc.

The networks just described may be considered as three, mainly additional, ways of speaking about radioactive events in the world we share. From our descriptions it should be clear that the common sense ontology, as Ogborn (see, e.g., Mariani and Ogborn, 1991) puts it, is basically correct and needs not to be changed at all (Klaassen, 1993). Students have to develop new meanings, intentions and beliefs, which, however, can only make sense if they can be related to and become embedded in the vocabulary they already know. To be able to fluently use the appropriate beliefs, meanings and intentions, according to the circumstances. One may call this process 'conceptual change', but then the term refers to a much more intricate and continuous process, than is usual in 'one-dimensional' status-changing or conflict strategies.

From in-depth protocol-studies of student-teacher discourse it has become clear that severe learning difficulties result if students and teacher are unaware of the fact that they are talking different 'languages', even though they might be using the same terms (e.g. Lijnse, 1992). Unfortunately, this appears to be quite common in classrooms. Teachers are often insufficiently aware of the network they use and therefore they misinterpret what students are talking about. As already said, this usually results in 'forced' concept transfer and thus in confusion and verbalism. This means, to our opinion, that the usual complaints about misconceptions and their 'resistancy to change' should not so much be judged as due to students' alternative frameworks, but largely be considered as consequences of 'bad' teaching.

8. FURTHER STEPS TO A 'DIDACTICAL STRUCTURE' FOR TEACHING ABOUT RADIOACTIVITY

From an analysis of (both Dutch and English) textbooks (Klaassen, Eijkelhof and Lijnse, 1990; Eijkelhof, 1990) we found that the standard way of teaching radioactivity, almost with no exception, is as follows: after a brief global orientation (if at all) on the topic, the micro-'facts' about nuclear physics and radioactivity are presented, to be applied subsequently in several contexts. Such teaching thus starts at the micro-level. An evaluation of this standard approach showed students to have all possible 'misconceptions' that have been reported sofar about particles and radioactivity. Which is unavoidable in view of the above. One may even ask whether it is possible at all to give the desired meaning to the micro-level, if the macro-level has not been elaborated sufficiently first.

If we compare the macro-network with the common sense network, we notice the following major differences. Students have to learn the meaning and use of the terms radiation and radioactive substance in situations where they are used to apply the term *radiation*. Secondly, and connected to this, they have to learn to give separate meanings to contamination and irradiation, which also relates to different sources (open/closed) and possiblities of protection. Though these are the major themes, they are connected in a network of relations that has to be sufficiently elaborated in order to become imbedded in students' 'living use of language'. The teaching problem thus becomes the design of activities that make students construct 'in freedom' these changes in meaning and intention.

Therefore, a new unit and teaching procedure has been developed with the following essential characteristics (Klaassen, 1993):

* first elaborating a global motivation for studying the topic and inventarising questions about it;
* starting from common sense notions and relations, recognizing and selecting relevant properties of objects, events and actions, in order to describe causal relations by means of generelized statements;
* establishing differentiations of meaning as much as possible on the basis of mutually agreed conventions;
* developing the macrolevel network first;
* evoking and using students' own questions as much as possible as local motives for reflection;
* having students design experimental activities to test their own hypotheses;
* elaborating and using this macronetwork in everyday contexts;
* postponement of the microlevel to the end (if at all);
* the teacher does not explain 'the facts' but guides the students in discussing activities and inventing experiments. His main activity is interpreting what students actually say and acting accordingly.
* students do not work from a textbook, but, in working from rather open worksheets, write their own textbook.

This teaching sequence has been designed in close cooperation with the teacher who participated in the study. He taught it twice and described and reflected on his own learning process. Its precise structure cannot be described here in further detail, but the central focus is on how to guide students to reinvent the ideas to be learned. Roughly, this is done as follows.
a) By knowing a lot of students' thinking about the topic, we know largely what sort of questions they will ask in what contexts. Teaching activities are very carefully designed and sequenced sothat most questions that are evoked by a certain activity, can indeed function as local motives for the next activity, because they are dealt with in the next activity.
b) Often this means that students themselves have to design a test that may give an answer. So, each activity is well prepared for by the foregoing and preparing for the following. Questions that are not immediately dealt with, are noted down by the students and the teacher and function as a way of making explicit 'how far we have come'.
c) In the start of the sequence, a convention is mutually agreed on, on the basis of experiences with objects that are and are not radioactive, to name an object radioactive, if a Geiger-counter ticks in the neighbourhood of that object. This empirical convention is from then on used in a disciplined way, to decide on matters about when and where something is radioactive. A crucial activity to differentiate the notion of *radiation* is, e.g., the activity in which an apple is irradiated by an X-ray tube. Most students are convinced that the apple will become radioactive, which means that the Geiger-counter should tick in its neighbourhood. However, the counter doesn't, which leads to the remark that it should be irradiated longer, etc. However, in the end, radiation doesn't seem to be able to make an object let a counter tick. However, what then has happened when *radiation* from Chernobyl did so with objects even in a far away country like the Netherlands.
The crucial point is that students are able to come up with questions, that can be decided on experimentally, largely according to their own design, provided that they discipline themselves in using the agreed on conventions. And that the teacher refrains from telling 'how things are'. Thus it can be said that students' own constructions are positively used.

Designing such a sequence is clearly a matter of classroom research. Sofar, it has been tried out and revised twice. The lessons were videotaped, transcribed and carefully analysed, both as far as students' and teacher's learning is concerned. Essential in the design, research and teaching process has been the development and use of a so-called scenario. This describes the relation between all the teaching and learning activities and expected processes that result from them in considerable detail. Such a scenario is an essential means of avoiding the usual gap between didactical theory and teaching practice. In fact, it is the didactical stucture we are looking for 'in statu nascendi'.

It turns out that the present scenario describes and to some extent predicts the actual learning processes in considerable detail, as far as insightful learning of the macro-network is concerned. This is why we think this method to be an important step forward. Further evaluation has shown that both the teacher and the students are very positive about this approach, as they had the feeling to be engaged in a worthwhile activity. Students appreciated the experience of not being forced to understand but of understanding, of together finding answers to (partly their own) questions by means of 'logical thinking', as did the teacher from his perspective. As researchers, it has given us the opportunity to gain insight what the phrase 'constructivist teaching and learning' could mean, as well as a conviction of how to proceed in finding solutions for the problems of teaching and learning physics.

9.FUTURE RESEARCH

How to enable a non-forced meaningful transition to the microlevel will be one of the topics of future research. It is very unlikely that this transition can be meaningfully made within the radioactive context only. In fact, a number of macronetworks should probably have been elaborated

first, in order to be able to develop a meaningful motive for students that asks for a microlevel description. This could mean that teaching about particles should better be postponed to higher grades. This further illustrates that a search for teachable didactical structures could well result in significant changes of the conceptual curriculum structure.
The insightful introduction of the particle idea, considered as a theoretical construct and not as a small piece of matter, still seems to be an unsolved problem that needs to be tackled. In the literature sofar, it seems to be largely unnoticed that constructivist approaches to introduce a particle model have only succeeded in developing a model of 'particles as small pieces of matter' that behave according to some new (strange?) rules. This could be a useful and even necessary intermediate notion, but then it should be recognized as such. And it should be made clear how the development into a 'theoretical' particle idea might be done later on.

The structure of matter, which involves not only the development of a particle idea, but also of molecular, atomic, nuclear models, etc, is one of the main strands of physics teaching. It should proceed according to a carefully designed 'bottom-up' conceptual development across the grades of (primary and) high school, based on teaching as mutual understanding. Of course, it is intertwined with other main strands as: causes and processes; conservation laws and symmetries; mathematising and modelling. We would suggest that developmental research should lead to the empirical description of a teachable longitudinal development of those main interlinked strands. Such research combines, as said before, the practical with the theoretical, the learning of students with the learning of teachers, the aims of physics teaching with their necessary pedagogy. It is not aimed at building 'grand theories' but at understanding and developing 'good teaching practice'. What else could we want?

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