Koos Kortland & Kees Klaassen (Eds.)

Designing Theory-Based Teaching-Learning Sequences for Science Education

Proceedings of the symposium in honour of Piet Lijnse at the time of his retirement as Professor of Physics Didactics at Utrecht University

[Faculty of Science
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Contents

Introduction

On Friday, October 9, 2009 a symposium was held on the occasion of the retirement, and thus in honour, of Piet Lijnse – now Emeritus Professor of Physics Didactics at the Freudenthal Institute for Science and Mathematics Education, Utrecht University, The Netherlands. The topic of this symposium, as outlined in the box below, clearly relates to much of the work Piet has been doing for decades. And the symposium can be seen not only as an event to honour him for his contribution to science education research, but also as a stimulus for continuing work of this sort.

Symposium

Designing Theory-Based Teaching-Learning Sequences for Science Education

The systematic study of design and evaluation of educational interventions – such as teaching-learning sequences – not only aims to provide solutions to complex problems in educational practice, but also to advance our knowledge about the characteristics of these interventions and the process of designing, implementing and evaluating them. Part of this knowledge reflects a local didactical theory: a didactical structure – an empirically based description and justification of the interrelated processes of teaching and learning – for teaching-learning processes for a certain topic (Lijnse, 1995). Beyond simply creating designs that are effective, a local didactical theory explains why designs work and suggests how they might be adapted to new topics and/or new circumstances.

The symposium will focus on the issue of designing theory-based teaching-learning sequences for science education: what can be considered a local didactical theory and how does such a theory inform the design of teaching-learning sequences?

Reference

Lijnse, P.L. (1995), “Developmental research” as a way to an empirically based “didactical structure” of science. *Science Education 79* (2), 189-199.

The first section of this book presents the contributions to the symposium: the lectures given by John Leach (also on behalf of Jaume Ametller and Phil Scott), Laurence Viennot, Robin Millar, and, of course, Piet Lijnse himself. Due to family circumstances and much to his regret, Jon Ogborn was not able to attend the symposium, but his intended contribution is also included. The second section of this book offers reprints of a number of key publications by Piet Lijnse, often referred to in the symposium contributions.

All contributions, of course, relate to the symposium theme, albeit it in different ways. John Leach, Jaume Ametller and Phil Scott (chapter 1) elaborate on how knowledge about teaching of specific scientific content, at a fine grain size (and thus useful for classroom practice), can be established and communicated to teachers in the form of ‘design briefs’. Laurence Viennot (chapter 2) focuses on ‘critical details’ and ‘common-sense, linear causal reasoning’ when dealing with experiments in inquiry-based science education. Robin Millar (chapter 3) addresses the assessment of learning outcomes (a forgotten dimension in science education research) and the character of the research-based guidance required to improve practice in the teaching of X (where X is any given science idea or topic). In contrast, Jon Ogborn (chapter 4) discusses science curriculum development as a practical activity, questioning the role of theory to inform the development of teaching-learning sequences. Finally, Piet Lijnse (chapter 5) reflects on his thirty-six years of work in physics education, which focussed on finding research-based ‘didactical structures’ that could potentially improve the teaching and learning of X’s, and result in the emergence of ‘didactical theories’ that are useful for curriculum developers and teachers. This effort is further elucidated by the reprints of some of his key publications (chapters 6-10) in the second section of this book.

Clockwise: Lijnse & Leach, Lijnse, Leach & Viennot, (part of) the audience, and Lijnse & Millar. Photographs courtesy of Fridolin van der Leck.

The symposium organisers – Koos Kortland, Kees Klaassen, Harrie Eijkelhof and Elwin Savelsbergh – wish to thank all those who contributed to and attended the symposium. We very much appreciated seeing you there. A special word of thanks to Robin Millar for his great help in co-editing chapters 2 and 5-10 of this book, written by the non-native English speakers at the symposium. And finally, we appreciate the cooperation of the editorial boards of the journals in giving us permission to reprint some of Piet’s key publications in the second section of this book.

October 2010
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1

Establishing and communicating knowledge about teaching and learning scientific content: The role of design briefs

Abstract

How can knowledge about the teaching of specific scientific content, at a fine grain size, be established and communicated? This is perhaps the central theme in Piet Lijnse's work. The focus of this paper is primarily methodological and conceptual. Its central premise is that much remains to be done to establish a reliable and agreed body of knowledge about the teaching of specific scientific content in such a way that students' understanding is maximised. The paper begins by presenting different strands of research on the teaching of specific scientific content in order to promote learners' understanding. Drawing on examples from design-based research and learning sciences research in North America, and European didactics research, we show how claims from such research are normally in terms of features of the learning environments at a large grain size, rather than in terms of features of specific content. The example of *design briefs* is then presented and exemplified, to illustrate one approach to establishing and communicating knowledge about the teaching of specific scientific content. The paper concludes with a discussion about how research on the design of science teaching can become more cumulative, enabling researchers and designers to draw explicitly upon findings from each other's work.

Introduction

> "I still remember my disappointment when, as a newly appointed didactician, I had to develop an innovative series of lessons to introduce quantum mechanics at secondary school. I turned to theories of education and educational psychology for help. However, hardly any such help appeared to be available, a frustrating result which unfortunately was (and is) in line with the 'traditional' scepticism of physicists concerning the 'soft' sciences." (Lijnse, 2000: p.309)

Piet Lijnse goes on to argue that decades of research in science education have not fundamentally changed the situation described in the above quotation, as there is still no broadly agreed body of knowledge about how to teach specific scientific content in order that it is understood by as many learners as possible. A cursory review of the international research literature, textbooks and curricula will indicate that there are some shared assumptions about teaching and learning science that arise from research in science education. Examples include:

- Learners' existing beliefs about the natural world influence the understandings that they develop as a result of science teaching – so teaching ought to take account of learners' existing beliefs.
- Learners' beliefs about what science is influence the understanding of scientific

concepts that they develop as a result of teaching.

- Learning is not a simple process of transfer of knowledge from a teacher to an individual, and teaching therefore needs to provide opportunities for the clarification of meanings.

We describe such shared assumptions as being at a *large grain size* (Leach & Scott, 2008). We use the term ‘grain size’ to describe the level of detail at which a process or practice is described – often in terms of specific content. The insights listed above are at a large grain size in the sense that they provide general orientations about teaching science (in terms of the influence of existing beliefs about the natural world and what science is, and in terms of a perspective on learning). We believe that such general insights have been valuable to attempts to improve the teaching and learning of science content. Some have been formulated into attributes of learning environments that need cultivation (Bransford *et al*., 2000: p.23-25). However, insights at a large grain size are not enough. More specific knowledge about the details of teaching and learning specific scientific content are needed – knowledge at a *fine grain size* (Leach & Scott, 2008). For example, though it is useful to know that learners’ existing beliefs about the natural world influence the understandings that are developed from teaching, it is *much more useful* to know the problems that arise in the teaching and learning of specific scientific content.

We agree with Lijnse that much remains to be done to establish a body of knowledge about teaching and learning specific content at a fine grain size.

The purpose of this chapter is to consider different strands of research that have been carried out on the teaching and learning of specific scientific content, the different kinds of knowledge that have been established from this research, and how such knowledge can be communicated between researchers (and others) to enable the research enterprise to become more cumulative. We will present an example to illustrate how knowledge about teaching specific scientific content to maximise learning can be established and communicated more explicitly.

1 Strands of research on teaching and learning specific scientific content: Possibilities and limitations

Teaching and learning specific scientific content has been a major focus of research in science education in both Europe and North America. In the introductory article of a recent special issue of the journal *Educational Psychologist*, Sandoval and Bell (2004) describe a tension between, on the one hand, classic psychological research methods which aim to produce widely applicable and replicable knowledge, and, on the other hand, detailed studies which illuminate issues in complex settings but where there are problems of transferring insights to other settings. They describe a trend in North American psychological research to address this tension by generating more practically useable insights for educational settings. They cite Anne Brown’s seminal paper, attempting “to bridge laboratory studies of learning with studies of complex instructional interventions based on such insights” (Brown, 1992: p.199), as the inspiration of a movement for ‘design-based research’.

Design-based research often refers to ‘learning environments’: “What systemic reengineering of learning environments might work better to teach students and teachers to respond to the opportunities rapidly unfolding in modern science?” (Kelly *et al*., 2008: p.3). The design principles that are advanced as a result of empirical work are at a large grain size. This can also be seen in accounts of the *Design Principles Database* (Kali, 2008). Kali lists examples of design principles which have been formulated as a result of evaluations of several different designs, with the intention of providing “... an intermediate step between scientific findings, which must be generalized and replicable, and local experiences or examples that come up in practice” (Bell *et al*., 2004: p.425). The listed examples include (Kali, 2008: p.429):

- *Pragmatic principle*: Enable students to give feedback to their peers.
- *Specific principle one*: Involve students in developing the evaluation criteria for the peer evaluation.
- *Specific principle two*: Ensure anonymity to avoid bias in evaluating peers.
- *Specific principle three*: Make the synthesis of the peer evaluation results visible for learners.

These design principles are at a finer grain size than those listed in the introduction, in that they are addressing a specific pedagogical practice (i.e. peer feedback). However, they remain at quite a high level of generality, in the sense that they refer to *all* peer feedback and presumably span from young learners to graduate students, involved in peer feedback activities in any area of their learning.

Much design-based research describes the successive refinement of designed educational interventions that is analogous to engineering methodology, the purpose of which is to test and systematically improve the fitness-for-purpose of a designed artefact (see, for example, Middleton *et al*., 2008; Hjalmarson & Lesh, 2008). It is harder to find accounts of the basis on which designs are developed in the first place. In presenting European approaches to didactical research in science and mathematics education, Ruthven *et al*. (2009) describe three programmes of work where theoretical and empirical insights about learning are systematically drawn upon at a fine grain size in the design process itself (for example, designing teaching to introduce decimal numbers in the primary school, or vector representations of balanced forces in secondary education). They differentiate between *grand theory* (addressing learning, or epistemology, in general terms) and *intermediate frameworks* (which draw explicitly upon grand theory to inform a particular practice such as designing mathematics or science lessons in school classrooms). They go on to present examples where intermediate frameworks have been used in the design process through the use of *design tools* (including Brousseau’s *adidactical situations*, Tiberghien and colleagues’ *modelling tools*, and Leach and Scott’s *learning demand tool*). The use of such design tools, together with teachers’ and designers’ professional insights, results in a design that is theoretically and empirically informed at both large and fine grain size.

Some researchers working in design-based research are involved in generating knowledge about teaching and learning specific content at a fine grain size. For example, Cobb *et al*. (2003: p.10) describe "theories developed during the process of experiment (that) are humble not merely in the sense that they are concerned with domain-specific learning processes, but also because they are accountable to the activity of design." Such domain-specific, instructional theories

> "… typically include sequences of activities and associated resources for supporting a particular form of learning, together with domain-specific, instructional theory that underpins the instructional sequences and constitutes its rationale. A domain-specific, instructional theory consists of a substantiated learning process that culminates with the achievement of significant learning goals as well as the demonstrated means of supporting that learning process." (Cobb & Gravemeijer, 2008: p.77)

We are sympathetic with Cobb and Gravemeijer's desire to articulate domain-specific instructional theories. However, in conducting our own work on designing and evaluating science teaching (and reviewing the work of others) we have been struck by how difficult it is to articulate knowledge claims about learning specific subject matter at a fine grain size. As Cobb and Gravemeijer imply, it seems to us quite difficult to articulate domain-specific instructional theories in the absence of sequences of activities and associated resources for supporting learning. As a community of researchers, we do not believe that we have achieved a way of achieving this articulation. As a result, different research groups do not draw upon findings from other groups because those findings are not clearly formulated or communicated. In the next section of this chapter, we present one approach to establishing and communicating findings about the design and evaluation of teaching specific content.

2 Design briefs as a tool for communicating knowledge about the teaching and learning of specific scientific content

In this section, we will explain what we mean by a design brief, and show how design briefs can be used to establish and communicate knowledge claims about the teaching of specific scientific content to maximise students' understanding.

We have described previously how we have used grand theory, intermediate frameworks and design tools (in terms of Ruthven *et al*., 2009) to inform the design of science teaching (Ametller *et al*., 2007; Leach *et al*., in press; Scott *et al*., 2006). We have used two design tools (i.e. learning demand and communicative approach) alongside teachers' professional knowledge to specify design briefs for teaching to address specific scientific content about introductory electric circuits, plant nutrition, and modelling the behaviour and properties of matter in terms of a simple particle theory.

The purpose of design briefs is to make explicit the design intentions for a piece of science teaching, explaining why particular design decisions have been taken. Design briefs address three aspects of the design specification of the teaching:

- the context for the designed teaching;
- the detailed content aims of the teaching;
- specification of the pedagogic strategies and sequencing of content to be used in the teaching.

Description of the context for the designed teaching

The authors of this chapter are from the UK and Catalonia, but the majority of our doctoral students are not from either of these places. As a result, we often have our assumptions about good science teaching challenged when discussing the design of teaching sequences, because many of our 'taken for granted' assumptions are not applicable in different national contexts. In addition, we have each experienced situations in international groups where it has been very difficult to establish good communication about teaching a specific aspect of scientific content, because of different tacit assumptions about the nature of the teaching challenge (for example, class size and levels of facilities, the educational background of the teacher, the content of the curriculum and the time available for teaching). For this reason, the first section of design briefs makes explicit contextual aspects and constraints that have to be addressed in a piece of teaching. This should enable researchers and others, when reviewing the teaching, to make some judgements about its applicability in different contexts.

This section of the design brief poses, and then answers, questions about the curriculum, students, teachers, and institutional constraints:

- *Curriculum*: What is the topic area, and how does it feature in the relevant curriculum? (What are the core ideas to be taught, what has been studied previously, what is to be studied later on in the curriculum?)
- *Students*: How old are the students, what is the ability profile of the class? Are there any features of students' expectations of science lessons that need to be taken into account in the design of teaching?
- *Teachers*: Are the teachers specialist science teachers or not, and if so what is their disciplinary background? Are there any features of the teachers' expertise or expectations of science lessons that need to be taken into account in the design of teaching?
- *Institutional constraints*: What is the class size? What teaching facilities are available? What time is available for the topic? What requirements are imposed by local regimes (e.g. assessment, homework)?

This part of the design brief is pragmatic, and is not informed by the use of intermediate frameworks or design tools. However, it is critically important to the success of any designed teaching that it does not transgress institutional constraints, and that it is not thought to be 'bad science teaching' by teachers and students.

A design brief that we have used to specify design decisions about introductory teaching on modelling the properties and behaviour of matter in terms of a simple particle model is presented in the appendix. This shows how we have answered questions such as these (and the others introduced in this section).

Specification of the content aims of the teaching

This part of the design brief specifies and justifies the content that is to be presented in the teaching. This decision is informed by an analysis using the *learning demands* design tool (which is described in detail in Leach & Scott, 2002). Learning demands arise from differences between the social language used by students to talk about a given aspect of the natural world prior to the teaching, and the social language to be introduced through the teaching. These differences are framed in terms of conceptual, ontological and epistemological aspects of the social languages.

Evidence about the social language to be introduced to students through teaching is taken from official sources such as the published curriculum or textbook, and evidence about the social language likely to be used by students prior to the teaching is taken from previously published research. This evidence is summarised in tabular form in the design brief, as can be seen in the appendix. The design brief presents a factual description of the curriculum, and gives commentary on it from a subject matter perspective (identifying, for example, any inconsistencies or omissions which result in logical inconsistencies in terms of the structure of the content). Learning demands are then specified in terms of conceptual, ontological and epistemological differences between the social languages, and tabulated. The learning demands are content specific. Finally, teaching goals are specified to address the learning demands.

It should be clear from the appendix that there is not a simple, algorithmic relationship linking from how some aspect of the curriculum is presented and some aspect of students' likely starting points, to a specific learning demand and a specific teaching goal. Rather, the process of formulating learning demands and teaching goals involves looking broadly at curriculum content and evidence about students' likely starting points. Consider, for example, the learning demand that students appreciate that all matter is made from particles. This arises from features of students' starting points including that gases may be thought of as 'nothing', or that particles themselves constitute the matter in gases, or that matter can 'appear' and 'disappear'. The teaching goals which introduce a model of the structure of matter, address this and several other learning demands – and there is a specific teaching goal that matter in each phase is made of the same set of particles.

Thus, this second section of the design brief includes design decisions which, although informed by intermediate theory and empirical evidence, go significantly beyond them.

Specification of the pedagogic strategies and sequencing of content to be used in the teaching

This part of the design brief specifies, and justifies, the pedagogic strategies and sequencing of content to be used in the teaching in detail. It draws upon our intermediate framework (a social constructivist perspective on learning for the purpose of informing science teaching in formal settings: Leach & Scott, 2003), and the *communicative approach* design tool (Scott *et al*., 2006).

Using our social constructivist perspective on learning for the purpose of informing science teaching in formal settings, we propose three fundamental issues that have to be addressed in the design of science teaching addressing specific content to maximise understanding. These are:

- *Staging the scientific story*: How is the target scientific model to be introduced to students?
- *Supporting student internalisation*: How will opportunities be provided for students to begin to try out new ideas with other students or the teacher, and how will the teacher check students' developing understanding?
- *Handing-over responsibility to students*: How will students become able to use newly-introduced content for themselves, with some opportunity for re-expression?

This section of the design brief therefore begins by specifying and justifying the design of the overall structure of the teaching intervention at a large grain size. This is exemplified in the design brief presented in the appendix. A design decision is justified to introduce a simple particle model ('Staging the scientific story'), using it to explain familiar properties of solids, liquids and gases ('Supporting student internalisation'), and then providing students with opportunities to use the model to explain familiar physical change processes ('Handing-over responsibility to students'). A further sequence of staging, supporting and handing-over is then justified, with additional content.

The next part of this section of the design brief justifies the sequence through which the teaching goals identified in the second section will be addressed. The sequencing is justified in terms of the epistemological structure of disciplinary knowledge (to explain why some ideas need to be introduced before others), evidence from the analysis of learning demands (to explain why some aspects of content are likely to be difficult for students to understand, and how this should be addressed), and the use of the communicative approach design tool (to explain the choice of communicative approach by the teacher in terms of the teaching goal). In addition, the pedagogic strategies to be used for addressing the teaching goals are presented and justified. We use the term 'pedagogic strategies' to mean different approaches to working on knowledge to address content-specific learning aims at a fine grain size (see Ametller *et al*., 2007). We suspect that there is a fairly limited range of pedagogic strategies that can be selected to address most content-specific learning aims in science, including:

- using formative assessment to make explicit to the teacher and students some aspect of students' knowledge;
- using an analogy or developing a model;
- using empirical evidence (data, observation, graph);
- setting up a conflict;
- presenting the science view, with a view to building straightforwardly on students' existing understanding;
- differentiating ideas, or contexts, and teaching when it is appropriate to use an idea.

The design brief presented in the appendix justifies a precise account of the properties of solids, liquids and gases to be agreed by students, and a precise account of the particle model of matter to be used, in order to generate explanations. The pedagogic strategies through which teaching goals are to be addressed (such as formative assessment and model building) are also justified.

The final part of this section of the design brief presents, and justifies, design decisions about communication with teachers via a teachers' guide (or, indeed, other mechanisms). The success (or otherwise) of the teaching is obviously dependent upon the teacher, while working to their own individual strengths and through their existing relationships with students, being able to implement key aspects of the design. Again, as for the second part of the design brief, the third section includes design decisions that are informed by intermediate theory and empirical evidence, but that go significantly beyond them.

What the design brief does not do

The design brief does not include precise specification of teaching activities that put pedagogic strategies into action. We refer to this specification as a *worked example* of how a design brief might be addressed. Many different worked examples which operationalise a single design brief might be produced; the broad sequence of pedagogic strategies would be the same, though the teaching strategies for putting pedagogic strategies into action could be different.

It is obviously possible for a worked example to succeed, or fail, in putting into action a design brief. In evaluating students' learning following science teaching, we therefore think that it is helpful to separate explicitly the effectiveness of the worked example, and the validity of the design decisions expressed in the design brief. If students do not appear to have understood content as planned in the design brief, it is necessary to consider explicitly the following possible explanations:

- *One or more specific teaching activities used in the worked example was not effective in addressing the design intention.* For example, classroom data may suggest that a particular analogy was not effective in supporting students' understanding, or that a strategy for enabling teachers to use a new activity or pedagogic strategy was not successful, or that some aspect of the teaching was not conducted consistently with the worked example. However, there might be relatively straightforward solutions in terms of revising the worked example to address the identified weaknesses.
- *Some aspect of the design intentions specified in the design brief proved unsound in some way.* For example, analysis of classroom data might lead to a decision that sequencing content in a particular way was inappropriate – and the solution in terms of the worked example would involve fundamental review.

In the next section, we will illustrate how we have used design briefs and worked examples to establish claims about teaching specific scientific content in ways that maximise students' understanding.

3 Using a design brief to establish and communicate knowledge about teaching specific scientific content: An example

In this section, we will describe how one aspect of the design brief was addressed through a worked example, and how students' understanding was evaluated following teaching. We will use this to illustrate how we believe knowledge claims about teaching scientific content at a fine grain size can be established and communicated.

Example: Modelling some properties of gases

The example that we are using is teaching students to use a simple particle model of matter to explain why gases have mass, and why gases spread to fill the available space. Section 2 of the appended design brief describes the details of the simple particle model that was used, and justifies choices in terms of the official curriculum and previous research on students' learning. Teaching goals are then presented, which include:

- Reinforcing students' knowledge of some characteristic physical properties of solids, liquids and gases – and introducing some new properties (compressibility, expansion on heating, diffusion).
- Introducing a simple particle model of matter to students, and helping them to appreciate and use conventions in the two-dimensional representation of features of the model.
- Using the model to explain characteristic physical properties of solids, liquids and gases.
- Supporting students in generating explanations themselves from the model.

Section 3 of the appended design brief describes and justifies pedagogic strategies through which these teaching goals are to be realised. Key features of the design are:

- Beginning the teaching with a formative assessment activity, to make explicit to students and the teacher how students explain the properties of matter based on prior teaching (and prior cultural experience).
- Having an overall structure of the teaching of content which begins with an authoritative presentation of the particle model, followed by showing students how to use the model to explain familiar phenomena, followed by handing-over responsibility to students for generating their own explanations using the model.
- The teacher using authoritative talk to introduce new ideas (such as features of the particle model of matter), and dialogic talk to explore students' ideas and clarify meanings (for example, when students are using the model to generate their own explanations).
- Emphasis is placed upon how particular properties of matter can be explained using specific features of the model: the shape and fluidity of solids, liquids and gases are explained in terms of the spacing and bonding of particles; density and compressibility is explained in terms of the spacing of particles.
- Evidence suggests that students have most difficulty in using the particle model

to explain the properties of gases, so a sequence of examples is proposed which includes explicitly treatment of conservation of matter, and mass, in change processes in the gas phase.

The worked example presents one approach to addressing the design brief.[1] It includes specific activities to address aspects of the design brief, such as the following extract from the teachers guide suggesting how teachers should introduce the difference in bonding in solids and liquids.

How do we explain fluidity?
In fluids (liquids and gases) the particles can move freely across one another, whereas in solids they cannot. Students often suggest that this is because the particles in solids are tightly packed together. The scientific explanation goes one step further in recognising that there are bonds between the solid particles holding them together. Thus it is impossible to push your hand through the desk. The bonds hold the particles together too strongly with some kind of attractive force. Hold up a piece of wire and pull hard on either end:

> *"See, I'm pulling on the wire but I'm not strong enough to snap it! I'm trying to pull apart the bonds between the particles but they're too strong!"*

Of course there are also bonds between the liquid particles, but these are much weaker.

> *"Can anybody think of any evidence that water particles are attracted to each other?"*

Pupils may suggest that water forms droplets, showing that water particles hold together in a group, rather than breaking away from each other freely as in the case of gases.

Some pupils might ask about the nature of the bonds. What exactly are they? At this point it is sufficient to refer to the bonds as 'a kind of attractive force' holding the particles together. Don't encourage them! A simple model for bonding is presented in a later unit.

In addition to addressing the content aims, pedagogic strategies and sequencing as set out in the design brief, the worked example is specific to the English curriculum and local norms and expectations about science teaching at the beginning of secondary schooling. Furthermore, the worked example includes a teachers' guide which was designed to address the design intention about communicating with teachers, expressed in the design brief.

It should be noted that the primary audience of the design brief is *other designers and researchers* whereas the primary audience of the worked example is *teachers*. Some designers, of course, may well be teachers; the point that we are making is that teachers wishing to use the worked example should not need to read the design brief. The worked example presents a sequence of activities, grouped into lessons, with guidance about communicative approach. Design decisions from the design brief are 'built in' to the worked example. There is no intention, however, to *restrict* teachers from being responsive to students' questions and motivations during teaching; on the contrary, such responsiveness by teachers is critical to our intermediate framework. The intention of the worked example is to enable teachers to

[1] Our worked example to address the appended design brief can be found at http://www.education.leeds.ac.uk/research/cssme/projects.php?project=88&page=1.

use their professional skills, personalities, and relationships with students in a manner consistent with design decisions in the design brief.

Evaluating the effectiveness of the designed teaching

We investigated the extent to which students at the end of the teaching sequence were able to use a simple particle model of matter to explain various physical properties of matter, using diagnostic questions. We will focus on two diagnostic questions here, relating to why gases have mass and why gases spread to fill the available space. These features of gases present students with the opportunity to use several aspects of the taught model of matter in their explanations, including the movement of particles in gases compared to liquids and solids, and the bonding of particles in gases compared to liquids and solids. Students completed the questions at the end of teaching. The first question was about weighing air. It presented a drawing of a level balance beam, with two rigid containers hanging from each end. Students were presented with three different scenarios as to what would happen to the balance beam if some additional air was pumped into one of the containers: 'The extra air would make the container *heavier*', 'The extra air would make the container *lighter*' or 'The extra air would make no difference to the mass of the cans'.

Students had to select the option that they thought was correct. They were then provided with a space to explain why they thought that this answer was correct. Next, they were asked to produce a diagrammatic representation to show the air in the container with *extra air* pumped in, and the container that had *no extra air* added. Finally, they had to explain their diagram. These questions enabled students to draw upon what they had been taught about verbal and diagrammatic representations of particles in gases.

The second question presented students with descriptions or representations of the behaviour and arrangement of particles in solids, liquids and gases (e.g. 'moving around freely in all directions', 'vibrate in a fixed position'). Students had to fit these descriptions into a table which presented aspects of the arrangement of particles in solids, liquids and gases (arrangement of particles, movement of the particles, distance between the particles, diagram of the particles). Students then had to produce an explanation as to why liquids take the shape of a container, but remain in the bottom of the container, in terms of the arrangement of particles in liquids. This question also enabled students to draw upon various aspects of the taught model of the structure of matter.

If the teaching goals expressed in the design brief had been achieved, we would expect students' answers to these questions to have the following features:

- They would associate mass with particles, and therefore expect the mass of a gas to increase if more particles were added to a fixed volume.
- They would associate matter with particles, and therefore produce diagrams showing that particles constitute a substance (rather than the substance existing in between the particles).
- They would explain the spreading of substances in terms of the movement of

particles, and bonding between the particles (gases spreading to fill available space, liquids spreading to fill available space while maintaining bonds between the particles, solids maintaining fixed shape due to the rigidity of bonding).

We have so far analysed data from two classes that have used the worked examples (29 and 32 students, 61 in total). In each case, students' responses to the post-test diagnostic questions have been analysed. As the purpose of the teaching was to address the teaching goals as previously described, post-test responses were analysed to consider the extent to which the teaching goals appeared to have influenced students' responses on the two diagnostic questions:

- Which elements of the scientific model did the students include in their responses (the existence of particles, the mass of particles, the relative absence of bonding between particles in gases compared to solids and liquids, the emptiness of the space between particles, the motion of particles)?
- What visual representations were used to answer the diagnostic questions (from continuum to the taught representation with verbal explanations, paying special attention to the spatial distribution of particles)?
- How consistently did students respond across the parts of the questions? This aspect of students' responses was taken as evidence of the extent of consolidation of students' ability to use the particle model to generate explanations.

Four common ways of using the taught model to respond to the questions were observed after teaching:

1 *Undeveloped model*: A student's response lacked one of the two fundamental ideas from the model: matter is made of particles, and particles have mass. Such responses often included incorrect visual representations, and responses were often not consistent across different questions (6 students; about 10% of responses).

2 *Model used without addressing distribution*: Gases were represented as consisting of particles which have mass, but the particles were not distributed around the container (17 students; about 28% of responses).

3 *Model describes distribution*: Gases were represented as consisting of particles which have mass, spreading out to fill the container. However, the relative absence of bonding between particles in gases was not mentioned in explanation of why gases spread to fill the container. Responses often used the taught visual representations of the particle model, though there were often inconsistencies between contexts (24 students; about 39% of responses).

4 *Taught model used virtually consistently*: Such responses contained almost all the elements presented in the design brief and the visual representation always followed the conventions presented in the teaching. Students' responses used a model of matter that could explain solids and liquids too, rather than treating gases as a 'special case'. Nevertheless explanations sometimes included minor inconsistencies usually related to the understanding of bonds between particles (10 students; about 16% of responses). Amongst these, only 3 students out of 61 referred explicitly to differences in the bonding between particles in gases compared to solids and liquids to explain distribution.

Explaining findings about the outcomes of teaching

We begin this section by reminding readers of the *design intentions* of the teaching as relevant to the gases example that we are discussing (as represented in the design brief), and the *expected outcomes* if the worked example (as enacted) succeeded in addressing the design intentions:

Design intentions (as encapsulated in the teaching goals and associated pedagogic strategies)	**Expected outcomes (from students' responses to the diagnostic questions)**
• Reinforcing students' knowledge of some characteristic properties of solids, liquids and gases – and introducing some new properties (compressibility, expansion on heating, diffusion). • Introducing a simple particle model of matter to students, and helping them to appreciate and use conventions in the two-dimensional representation of features of the model. • Using the model to explain characteristic physical properties of solids, liquids and gases. • Supporting students in generating explanations themselves from the model. • Doing all of this through the specified pedagogic strategies (formative assessment, authoritative presentation followed by handing-over, dialogic talk for exploring ideas and clarifying meanings, placing special emphasis on gases).	• The particles in gases (and all matter) constitute the substance. • Particles have mass, so air makes things heavier. • The spreading of gases is explained in terms of the motion and spacing of particles, plus the absence of bonding between particles. • The model should be used consistently across parts of the diagnostic questions.

The learning outcomes described in the last section do not provide strong evidence that the design intentions that we have been discussing were achieved securely: only 43% of students' responses used the taught model in response to the diagnostic questions in a way that was (almost) consistent with the teaching goals (i.e. coding categories 3 and 4 above). In order to explain why this might be, we turned our attention to how the teaching was enacted. The teaching was video-recorded and field notes were kept. In addition, we conducted interviews with the teachers prior to, and during, the implementation of the teaching. The interviews, video record and field notes were analysed to determine the extent to which the teaching as conducted was consistent with the teaching goals expressed in the design brief.

The two groups studied in this paper were taught by two different teachers. The first teacher (Penelope; n = 29) was an experienced chemistry teacher, the second (Sylvia; n = 32) was in her third year of teaching. The students in Sylvia's class were assessed by the school as higher achieving in science than those in Penelope's class. Both teachers were members of staff in schools that had agreed to participate in a project where three designed worked examples would be used by all science teachers. They had each therefore attended a presentation where the three worked examples were introduced in overview. In addition, they had attended a presentation about the specific design intentions of the worked example addressing the introduction of a simple particle model of matter.

Both teachers followed the proposed teaching sequence, and the structure and sequence of activities is almost the same in both cases. However, there were significant differences between the way in which the teaching was enacted, and the design intentions of the design brief. In interviews with the researchers, Sylvia was very positive and wanted to follow it as much as possible, whereas Penelope was more critical of some aspects (particularly the amount of content to be covered in a short period of time). During implementation, Sylvia allowed more time for student talk (as in the worked example), whereas Penelope rearranged practical work and was more directive during classroom discussions. During group activities proposed in the worked example, both teachers engaged students in dialogic talk as proposed in the worked example, and the overall amount of dialogic talk was about the same in each classroom. Both teachers introduced the particle model to students in a manner broadly consistent with the worked example.

Key differences between the teaching as conducted, and teaching goals expressed in the design brief, are as follows:

Matter is made of particles with mass	Both teachers followed the worked example reasonably closely.
The arrangement of particles explains the behaviour of matter	Neither teacher spent much time showing students how the simple particle model could be used to explain the spreading of gases, by emphasising that the spaces between particles in gases are empty (though both mentioned the absence of bonding between particles in gases; see below). Penelope included the spacing of particles in her lesson summaries; Sylvia rarely mentioned it.
Bonding between particles	Both teachers mentioned the concept of bonding, though neither placed as much emphasis on it as suggested in the worked example. Sylvia used bonding in explaining changes of state, but did not include bonding in her summaries of the model. Penelope addressed bonding when building the model in the first two lessons but hardly mentioned it when discussing changes of state.
Representation of particles	Both teachers introduced the two-dimensional representation of the particle model. In addition, Sylvia used role play. However, Penelope placed more emphasis than Sylvia in revisiting the basic elements of the model (arrangement, movement, bonds and space between particles) during summaries in lessons. Sylvia's emphasis was upon the movement of the particles (as demonstrated through the role play), rather than on showing how various aspects of the model could be used to explain aspects of the behaviour of solids, liquids and gases.

Based on the evidence presented in this section, we believe it is possible to advance knowledge claims about teaching specific scientific content at a fine grain size. The claims address the introduction of a simple particle model of matter (as described in the design brief) to English students at the beginning of secondary education (age

11-12). We advance the following claims when using an introductory particle model of matter (as described in the design brief) to explain the physical properties of gases, with English students aged 11-12:

- If bonding between particles is not treated explicitly across solids, liquids and gases, it is likely that many students will not explain the spreading of gases using the model.
- If features of two-dimensional representations of the particle model are not explicitly mapped on to verbal and other descriptions of the model, it is likely that significant numbers of students will not be able to generate two-dimensional representations to explain the behaviour of gases (even though they may be able to recognise presented representations).
- If a worked example requires teachers to place emphasis on aspects of content different from their normal teaching approaches, it is likely that significant resources will be required to enable teachers to change their practice.

4 Discussion

Knowledge claims that are established from work such as that described in this paper are by their nature very localised: they refer to detailed aspects of a particular content domain, as introduced to students of a given age who are working through a particular curriculum, taught by teachers with characteristic backgrounds, in school systems with particular norms and expectations. When groups of such claims are established and communicated around a particular content domain, it should be possible to formulate what Cobb *et al*. (2003) referred to as *domain-specific instructional theories* – that is, groups of interrelated claims about teaching and learning specific scientific content at a fine grain size.

However, this raises two fundamental questions. The first is whether claims about teaching specific scientific content at a fine grain size are always so localised as to make it virtually impossible to use them to inform the design of teaching in other situations. The claims that we have advanced in this paper are strongly contextualised towards students who are following a particular curriculum. To that extent, other designers wishing to draw upon work such as this will always have to make judgements about the extent to which contexts are similar. We can see, for example, that designers working to a curriculum in which particle models of matter are first introduced to students who are significantly older than age 11-12 might reach different conclusions than ours about the difficulty of enabling students to explain the spreading of gases using a particle model. We can also appreciate that differences between curricula might result in designers using particle models that are significantly different from the one that we used, perhaps reducing the relevance of some of our claims. Such judgements cannot be made, of course, unless claims are articulated in the first place.

The second fundamental question is whether it is possible to communicate claims about teaching specific scientific content at a fine grain size without presenting all aspects of design briefs and worked examples. This paper is long, particularly given the size of the appendix (and the content of the worked example which is on the internet), yet the claims which were proposed at the end of the last section are localised and modest. However, we do not see how other designers/researchers can understand and judge claims such as these without understanding the rationale for the way in which teaching was designed (i.e. the design brief), and how teaching was actually conducted. Claims such as these about teaching and learning scientific content at a fine grain size are important. If they are not articulated and subject to scrutiny by the academic community, it is hard to see how research on teaching and learning scientific content can be cumulative, or how it might be used to inform decisions about the curriculum, or recommended teaching practices, or teacher education.

Piet Lijnse (2000; p.310) argues that the 'didactical quality' of science teaching is often not addressed. However, we are not aware that Lijnse has defined what is meant by didactical quality in the literature. We believe that one approach to defining didactical quality might be achieved by establishing groups of related claims about the teaching of specific scientific content at a fine grain size (and building domain-specific instructional theories), and determining the extent to which teaching is consistent with those theories.

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Appendix

Design brief for teaching to explain change processes using a simple particle model of matter

July 2009

Section 1: Description of the context for the designed teaching

This section specifies the curricular and institutional context in which the teaching is to take place.

Key questions addressed	Explaining change
Curriculum: What is the area, and how does it feature in the relevant curriculum? [What are the core ideas to be taught, what has been studied previously, what is to be studied later on in the curriculum?]	Students classify materials as solid, liquid and gas based upon observable properties at KS2. They are introduced to technical vocabulary for changes of state (melt, boil, evaporate) in the context of changes of state of water. They are not formally introduced to models of the submicroscopic structure of matter. The teaching sequence addresses the following part of the KS3 national curriculum for science (followed by students in maintained schools between the ages 11 and 14): *Chemical and material behaviour* • The particle model provides explanations for the different physical properties and behaviour of matter • Elements consist of atoms that combine together in chemical reactions to form compounds Content addressing periodicity is not included in this unit. Students are introduced to a simple model of matter which portrays atoms as hard balls in interaction with one another. Some characteristic properties of solids (e.g. fixed shape, strength), liquids (e.g. fluidity, takes the shape of the container) and gases (e.g. spreading, lack of fixed shape) are explained using the model. Selected physical (e.g. change of state) and chemical (e.g. formation of new substance on reaction) change processes are explained in terms of changes in the interactions between atoms, though no mechanism for bonding is explicitly introduced. The model is used to account for the conservation of mass during physical and chemical change processes.

	The model of matter introduced at KS3 is developed at KS4 to portray atoms as a nucleus (containing protons and neutrons) surrounded by electrons in orbital shells.
Students: How old are the students, what is the ability profile of the class? Are there any features of students' expectations of science lessons that need to be taken into account in the design of teaching?	Students aged 11-12, in their first year of secondary education, are often taught in groups that include the full ability range, though increasingly students are divided according to ability at an early stage. Students are used to a significant amount of practical work in science lessons. They are familiar with small group work. This teaching sequence has not been designed with any particular ability range in mind, though the content and pace of the lessons is challenging and perhaps best suited to more able groups of students.
Teachers: Are the teachers specialist science teachers or not, and if so what is their disciplinary background? Are there any features of the teachers' expertise or expectations of science lessons that need to be taken into account in the design of teaching?	Teachers are specialist science teachers, though their subject specialism may be physics or biology rather than chemistry. Teachers will expect lessons to include a significant amount of student practical work (as much as 20-30% of teaching time), and are skilled in organising this. There are likely to be differences in the familiarity and skill of different teachers in conducting discussion-based activities. Some school cultures allow teachers considerable autonomy to use time flexibly to cover content; other schools control this very tightly. It will therefore be necessary to make explicit the degree of time flexibility intended, when worked examples of teaching are produced.
Institutional constraints: What is the class size? What teaching facilities are available? What time is available for the topic? What requirements are imposed by local regimes (e.g. assessment, homework)?	There is considerable variation in the way in which students are introduced to the content covered in this teaching sequence. Until recently, many schools did not introduce particle models of matter until the age of 12/13 or even 13/14, though now the trend is increasingly to introduce models of the structure of matter from age 11-12. Some schools introduce a particle model of matter to model the solid, liquid and gaseous state, then use it to explain change of state, leaving the treatment of chemical change until later at KS3. Class sizes vary considerably, from around 22 to as many as 34. All science lessons are normally taught in rooms that are equipped for standard practical work. Most laboratories will have access to the Internet and interactive whiteboards. Students' performance will normally be assessed at the end of a topic through a formal test, and test results will often be used by the leadership of the school to monitor pupils' progress prior to national testing at age 14 (SATs). The culture of 'teaching to the SAT' is well established in many schools.

Section 2: Specification of the content aims for the teaching

This section presents content goals for the teaching sequence, by analysing learning demands for a particular area of the curriculum.

Curriculum content [Taken from official curriculum documents, plus textbooks. Content is presented, with commentary]	**Evidence about students' likely starting points (see review articles by Driver, 1985; Andersson, 1990; Johnson, 2000; 2002)**	**Learning demands**	**Teaching goals**
Conceptual model underpinning the topic: The introduction and use of a simple particle model of the structure of matter lies at the heart of the curriculum. The model is introduced to explain some characteristic features of matter in the solid, liquid and gaseous phases. It is then used to explain some aspects of the behaviour of matter in physical and chemical change processes. The model normally presented portrays matter as being made of 'particles', which are submicroscopic 'balls' in interaction with each other: • The generic notion of 'particles' is often not differ-	*Conceptual and ontological starting points:* A few students may not differentiate between *objects*, and the *material* from which objects are made (e.g. Johnson 1998) – for example they may find it hard to appreciate that steam and ice are *the same substance*; Many students will be familiar with words and representations for the structure of matter from the common culture, though the meanings understood are likely not to correspond with the meaning targeted in the teaching. Many students will reason in terms of familiar prototypes for the properties of gases (e.g. air), liquids (e.g. water) and solids (e.g. wood). When introduced to a particle model of the structure of matter, several characteristic difficulties are well-documented, and	*Conceptual and ontological learning demands:* • Appreciate that matter includes all solids, liquids and gases – and the same models can therefore be used to explain the properties of substances in each phase; • Appreciate that all matter is made from *particles* – the particles constitute the matter; • Develop a notion that *particles* are submicroscopic objects that, through their arrangement, can explain the properties and behaviour of matter; • Appreciate that the most fundamental parti-	To *reinforce* students' prototypical understanding of solids, liquids and gases, and the observable properties of each phase (shape, rigidity, spreading out). Students are likely to have familiarity with these properties, and they are addressed in previous teaching. Agreed descriptions of these properties will enable the conceptual model underpinning the topic to be used to generate explanations in familiar contexts. Next, properties that are likely to be unfamiliar *are introduced* (compressability, expansion on heating, diffusion), in order to enable other features of the conceptual model introduced in the topic (space between particles, movement of particles) to be used to generate explanations. To *introduce* a model of the structure of matter that is internally coherent, and can be used to explain selected aspects of the properties of matter, as well as the nature of physical and chemical change processes. The

entiated into atoms, molecules, etc. in the context of physical change – this differentiation is made when required to explain chemical change processes; • There is a finite number of types of atom; • In solids, the particles are touching and joined in a fixed way – this explains why solids keep their shape and are resistant to breakage; • In liquids, the particles are touching and attracted to each other, but free to 'roll over' one another – this explains why liquids are not easily compressible, and take the shape of containers; • In gases, the particles are very far apart – this explains why gases spread out to fill the available space; • Atoms/particles are in constant motion; • The curriculum does not include an explicit mechanism for bonding – though it is necessary to refer to bonding in order to explain the properties of materials, and physical and chemical change	experienced by many students age 11-14: • Many students attribute features of the macroscopic properties of a substance to the particles ('the atoms expand on heating', 'copper atoms are brown'), rather than appreciating how the properties of matter can be explained in terms of the arrangement of particles; • Many students have a naïve model of gases as 'nothing' – they do not therefore assume that gases can participate in chemical change processes ('How can something as solid as wood be made from a gas?'); • When modelling the gas phase, many students do not recognise that *the particles themselves* constitute the gas, thinking instead that the gas *surrounds* the particles; • Many students find it difficult to imagine the size and scale of atoms; Additional difficulties arise when using the particle model to explain chemical change processes: • Many students do not appreciate how the particle model can be used to explain the difference between *substance* and *mixture*, and *element* and *compound*; • Many students do not have a notion	cles are *atoms* – of which there are a finite number of types – which constitute all matter; • Appreciate that atoms cannot be created or destroyed, and that atoms have mass – therefore, matter is not created or destroyed in change processes; • Through understanding of the simple particle model of matter, appreciate the difference between *chemical substances* and *mixtures*, and *elements* and *compounds*. *Epistemological learning demands:* • Understand that the simple particle model of matter introduced through the teaching has been developed to explain a selected set of properties of matter – it is not simply a description of how matter 'really is'. • We use characteristic systems to represent features of the model in	model has the following features: • Matter is comprised of *particles*; • The properties of matter, including during physical and chemical change processes, can be explained in terms of the arrangement of particles; • The most basic particle, in this model, is the *atom*; • There is a finite number of different kinds of atoms; • Atoms can be *bonded* to each other; • Particles are in constant *motion*; • *Energy* changes are associated with changes in the arrangement of particles. This model broadly corresponds to that described in the curriculum. However, additional features such as *bonding* have been introduced to enable coherent explanation of the different properties of solids from liquids and gases. To *support* pupils in using the model to generate explanations of the observable properties of solids, liquids and gases (shape, rigidity, spreading out, compressability). This teaching goal is emphasised with the intention that students will come to think about the particle model as a tool for explaining and predicting the behaviour of phenomena, rather than merely describing phenomena.

processes; • Physical change processes (such as phase changes) can be explained in terms of making and breaking bonds between particles of the *same kind*; • Chemical change processes (where new substances are made) can be explained by making and breaking bonds between atoms of *different kinds*; • Matter is conserved in change processes; • Changes in energy are associated with change processes.	of a *chemical substance*, and therefore do not appreciate the idea that 'new substances are formed' in chemical change processes ('Melted chocolate is a new substance – you can't get it back to how it was before!) (Johnson 1998); • Many students use everyday explanations of chemical change (Andersson, 1990) – matter can 'appear' and 'disappear', matter can exist in objects and be 'revealed' in certain circumstances (e.g. cold, wet weather 'brings out' the rust in an iron nail); *Epistemological starting points:* Students are unlikely to have been introduced explicitly to the nature of modelling in science. Following from the conceptual and ontological points highlighted above, they are likely to think of models as accurate *descriptions* of the material world, without appreciation of their purposes and boundary conditions (e.g. Driver *et al.*, 1996). *Previously taught content:* Students will have previously classified materials as solid, liquid or gas, based upon similarity to prototypes ('it's like wood') or the use of simple criteria ('you can't put your hand through it').	diagrammatic terms; the diagrams that we use are not figurative representations of particles. • More sophisticated models have been developed, and will be introduced in subsequent teaching, that build upon this model to explain a wider range of properties of matter.	To address specific misconceptions common when pupils are first introduced to models of matter: • Matter in each phase is made of the same set of particles; • The properties of matter can be explained by the *arrangement* of particles (rather than particles having properties which are the same as the macroscopic substance); • The matter in gases consists of particles with spaces in between; • Substances, and therefore mass, are conserved in physical change processes; • Particles, and therefore mass, are conserved in chemical change processes. To *introduce, and support the development of,* the use of the model to define: • Substances vs. mixtures; • Elements vs. compounds. This teaching goal addresses specific curriculum content, providing an opportunity to use the particle model to differentiate between key groups of materials. To *draw attention to, and to emphasise,* the idea that: • Two-dimensional diagrams of particles represent features of the model through conventions; they are not figurative representations. • More sophisticated models of matter can be used to explain a wider variety of the

			properties of matter. This teaching goal is included to tackle explicitly students’ lack of appreciation that scientific models can be judged according to their explanatory power, rather than whether they represent ‘true descriptions’ of the nature of some aspect of the material world.
Other aspects of content: To address explicitly the nature of models of matter in science, illustrating the nature of modelling, and explaining that more sophisticated models of matter will be needed to explain a wider range of the properties of matter.	As above.	As above.	As above.

Section 3: Specification of pedagogic strategies and sequencing of content

This section presents in overview design decisions about the sequencing of content and pedagogic strategies employed for supporting students' learning at a fine grain size – but falls short of developing particular teaching activities and addressing their staging (Leach & Scott, 2003) in lessons.

Aspect of the teaching to be designed	**Explaining Change teaching**	**Rationale and justification**
Overall structure of the teaching intervention (large grain size)	**1** *Staging the scientific story*. The simple particle model is introduced. **2** *Supporting student internalisation*. It is used to explain (mainly familiar) properties of solids, liquids and gases. **3** *Handing-over responsibility to the students*. Students then use the model to explain familiar physical change processes involved in change of state. **4** *Staging the scientific story*. The model is extended to incorporate changes in the arrangement of bonding to define chemical change. The notions of mixture / substance, and element /	This overall structure of the teaching sequence at a large grain size is informed by an *intermediate framework* (i.e. the social constructivist perspective on teaching and learning science in formal settings outlined by Leach & Scott, 2002). Knowledge is conceptualised as existing on both a social and a personal plane, and learning is conceptualised in terms of the development of knowledge on the personal plane that enables learners to participate appropriately in activities on the social plane. For this reason, the teaching will involve a mixture of authoritative and dialogic talk. Authoritative talk will be used when the teacher is presenting information on the social plane, whereas dialogic talk will be used to exploring students' ideas and clarify meanings in order to support students in developing knowledge on the personal plane. The difficulties that students commonly experience when using particle models to describe the properties of matter, and account for physical and chemical change processes, are well documented. Students appear to find modelling involving *the gas phase* more difficult than that involving the solid and liquid phases. In addition, many students use everyday explanations of chemical change processes (e.g. 'it just appeared'). A simple particle model of matter is therefore introduced to explain characteristic properties of matter in the solid, liquid and gas phase, prior to using the model to explain change processes. It is then used in the context of physical change processes, and finally chemical change processes. At various points in the design, opportunities for addressing the difficulties students experience in understanding the nature and structure of gases are identified.

	compound are explained in terms of the model. **5** *Supporting student internalisation*. Students practice explaining the above terms using the model. **6** *Handing-over responsibility to the students*. Students then use the model to explain progressively more complex chemical change processes.	
Sequencing of teaching goals from section 2, and selection of pedagogic strategies (large and fine grain size)	**1** Formative assessment: the properties of solids, liquids and gases; the internal structure of solids, liquids and gases; how does internal structure explain the properties of solids, liquids and gases? **2** Building consensus: familiar properties of solids, liquids and gases.	**1** This formative assessment has multiple purposes. Firstly, it enables students and the teacher to recognise students' understanding of previously taught content about the properties of the phases of matter. However, there is evidence that many students have ideas about the internal structure of matter prior to teaching (and the way in which this explains various properties of matter); the assessment activities enable these ideas to be made explicit to both students and teachers. The communicative approach used by the teacher during this phase will have significant *dialogic and interactive* phases – probing and clarifying meaning. **2** In order to introduce a particle model to explain the properties of matter, it is necessary for the class to have an agreed description of those properties. Students have already been introduced to some properties of matter from their previous schooling: • The shape and fluidity of solids, liquids and gases are contrasted to enable explanation in terms of the ability of particles to move relative to one another. • The density of solids and liquids, compared to gases, is used to enable discussion of the relative spacing in particles. Formal definitions of density are not used; rather 'heaviness' and 'lightness' for size are referred to.

In addition, the relative compressibility of gases, compared to solids and liquids, is introduced as it is easy to demonstrate, and the particle model can be used to explain these properties in terms of the spacing of particles. Two further properties of solids, liquids and gases are introduced:

- Expansion of solids on heating is introduced to enable explanation in terms of the movement of particles.
- The diffusion of liquids and gases are introduced to enable explanation in terms of the movement of particles.

Communicative approach: significant *dialogic and interactive* probing and clarifying meaning. *Authoritative and interactive* and *dialogic and non-interactive* for agreeing shared meanings.

The description to be used has the following features, which enable explanation in terms of the particle model that is being introduced:

Property	**SOLIDS**	**LIQUIDS**	**GASES**
1. Compressibility	cannot be compressed	cannot be compressed	can be compressed
2. Shape	fixed shape	shape of container	spread into space
3. Fluidity	can't move hand through	can move hand through	can easily move hand through
4. Density	'heavy' / 'light'	'heavy' / 'light'	'light'
5. Expansion on heating	expand	not mentioned	not mentioned
6. Diffusion	not mentioned	diffuse into one another	diffuse into one another

The model presents all matter as being made of particles. Particles are represented as hard balls which are in constant motion. The particles in solids and liquids are touching each other, whereas the particles in gases are spaced widely apart. The particles in solids are represented as bonded together, so they are not free to move in relation to each other, whereas the particles in liquids are represented as free to 'roll over' each other. The particles are represented as being in constant motion: vibrating about a fixed point for solids, and moving and colliding for liquids and gases. Analogies to familiar situations might be proposed to make the model plausible, for example:

- Solids: the particles are like a pile of ping-pong balls, or oranges stacked in the supermarket, that have been glued together. [This does not account for the *movement* of particles.]

- Liquids: the particles are like ‘a bag of marbles’ – touching, but free to roll over each other. [This does not account for the *movement* of particles.]
- Gases: the particles are like tennis balls, being fired in all directions by tennis serving machines placed all around a room.

3 Particle model of matter introduced to explain the agreed properties of matter.

3 The agreed properties of matter in its various phases are explained as follows:

Property	**SOLIDS**	**LIQUIDS**	**GASES**
1. Compressibility	cannot be compressed; particles are touching	cannot be compressed; particles are touching	can be compressed; particles separated by space
2. Shape	fixed shape; particles are bonded	shape of container; particles can roll over one another	spread into space; particles moving in all directions
3. Fluidity	can’t move hand through; particles are bonded	can move hand through; particles can roll over one another	can easily move hand through; particles are separated
4. Density	various; the particles are touching	various: the particles are touching	‘light’; there are spaces between the particles
5. Expansion on heating	expand; the particles vibrate more, and hence separate	not mentioned	not mentioned
6. Diffusion	not mentioned	diffuse into one another; the particles move, collide and mix	diffuse into one another; the particles move, collide and mix

4 Practice at using the explanatory model

4 Students are then introduced to familiar processes – changes of state from ice to water to steam – which they are required to explain using the newly-introduced particle model. This process provides a vehicle to address the conservation of matter (and hence mass), given that many students appear to think of matter ‘appearing and disappearing’ in change processes involving gases. It also allows for the introduction of the role of energy in changing the movement of particles. *Dialogic and interactive*

		for clarifying students' meanings in small groups; *authoritative and interactive* for presentation of modelling.
	5 Open up a problem: how can you tell if new 'stuff' is formed during change processes?	**5** There is evidence that many students do not have a notion of 'substance' that enables them to recognise that, for example, ice and water are the same substance. This problem has been exacerbated by some teaching approaches that suggest that observable features of matter can be used to identify if new substances have been formed, or to differentiate between *mixtures* and *'pure things'*. The purpose of this phase of the teaching, therefore, is to enable students to appreciate what a substance is *in terms of the particle model of matter*, to use that understanding of substance to differentiate between mixtures and substances, and to use it to understand the significance of *chemical change* (and how these differ from *physical changes*). By considering observable features of familiar change processes, students are presented with a conflict: it is often not possible to identify whether new 'stuff' is formed during change processes. This opens up a problem which can be solved with the newly-introduced particle model of matter. The approach involves opening up a problem: *how can you tell if new 'stuff' has been formed*? *Dialogic and interactive* for probing and clarifying meanings.
	6 Extend the particle model to explain the formation of new 'stuff', and introduce key terms (physical and chemical change, substance and mixture).	**6** The example of preparing iron sulphide is used to show how the simple particle model can explain the formation of a new substance. Iron sulphide is used as a context as its observable properties differ from those of iron and sulphur (e.g. colour, attraction to a magnet), and all products and reactants are in the solid phase. Furthermore, as the stoichiometry of the reaction is 1:1, a simple and accurate representation in terms of particles can easily be produced without the necessity of explaining stoichiometry. We are not aware of another example of a chemical change in the solid or liquid phase, that has 1:1 stoichiometry, that can be easily demonstrated, and where there are easily observable differences in the properties of products and reactants. *Authoritative and interactive/non-interactive* for presentation of the model.
	7 Practice at using the model to explain progressively more complicated chemical change processes: • In one phase; • Involving gases;	**7** Students experience most difficulty in understanding both physical and chemical change processes involving the gas phase. A sequence of examples is therefore proposed: • Modelling chemical change processes in just one phase; • Modelling chemical change processes involving a phase change; • Including a specific focus on the conservation of matter, and mass, in chemical change processes involving the gas phase. *Dialogic and interactive* for probing and clarifying meanings; *authoritative and interactive/non-*

	• Involving gases to address conservation.	*interactive* for presentation of appropriate modelling.
Teachers' Guide	Develop a Teacher's Guide to highlight teaching activities, along with their rationale, in such a way as to maximise the likelihood that the teaching will be conducted in a manner consistent with its design intentions, and the professional expertise of the teacher.	Given that it is usually unfeasible to give anything but the most cursory training to teachers who are going to implement teaching sequences, the main means of communication is therefore a teachers' guide. This might be developed in written form for distribution on paper or via the internet, or alternatively in digital form involving video clips of activities to illustrate possible approaches. Given resource limitations, we decided to go for a written format for the Teachers' Guide, which has the following design features: • Background. This presents, concisely, the approach adopted in the teaching, plus the content that students should have been exposed to during prior teaching. • Design features of the teaching are presented alongside actual teaching activities. This is intended to maximise the likelihood that teachers engage with the design rationale at the same time as preparing to teach specific content. • Dialogic Hot Spots. These are highlighted with icons. An interactive and dialogic communicative approach is relatively uncommon in most science classrooms, and this aspect of the design of the teaching is therefore highlighted especially prominently. • The teaching will often be conducted by teachers who are not specialists in chemistry. Although most will be very familiar with the content addressed in the unit, many will therefore have limited *pedagogic content knowledge* to draw upon (e.g. knowledge of common difficulties experienced by students, and effective ways of addressing these difficulties). Furthermore, some may not be clear how the KS3 model is developed in future teaching. Some commentary is therefore included alongside activities highlighting 'good questions to ask' students, and ways of dealing with common difficulties.

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2

Physics education research and inquiry-based teaching: A question of didactical consistency

Abstract

It has often been argued that using simple experiments with students can improve children's and students' interest and attainment levels in science. This view underpins some strategies that aim to promote physics and to influence young people in their professional orientation. Such a practice may be seen as a good way to show children or older students how science works, by placing them in a context in which they can be active (cf. 'active hands-on learning'). Various labels designate particular ways of using such experiments: 'physics by inquiry' and 'inquiry-based science education' are most often referred to. I will first recall the main ingredients of such approaches: they make ample room for the students' intellectual activity; therefore, a question is to be solved, taking into account the learners' prior expectations; discussions take place between the students and/or between the students and the teacher (or a 'mediator'); any conflict between what was expected and what has been observed is negotiated. In any case, the goal is that the students should gradually reach a view that is compatible with accepted physics, and/or formulate a new question.

I will then illustrate and discuss a series of *caveats* concerning the recommended events just listed. Some of these *caveats* have long been formulated by researchers in this domain: in particular, the outcome of an experiment may be denied, or cognitive conflicts may be by-passed by students. Furthermore, I will illustrate that, once one accepts the series of consensual viewpoints just enunciated, a wide range of strategies remains open. Although it would seem, given ritualistic practices, that a given 'simple experiment' conveys a single message, it is possible to deeply change its meaning by changing apparently small details. These 'critical details' can be determined in relation to a deliberate spotlighting of the content, chosen on the basis of a thorough consideration of the students' prior knowledge and common ways of reasoning. A series of examples will be given, respectively on Archimedes' interaction, magnetic and gravitational fields, and a siphon. This last device will serve to exemplify one of the roots of ritualistic practices, with corresponding limitations: the *echo-explanation*s of experts, explanations that adopt the same pattern as is dictated by common ways of reasoning – here, linear causal reasoning.

The discussion will then focus on more ample research-based innovative settings, or 'didactical structures' (Lijnse, 1994), already published in research literature. The aim is to draw attention to the need to insert inquiry-based strategies – in the sense that has often been put forward – into a more complete consideration of students' needs, if students are to attain conceptual achievement and a degree of intellectual satisfaction beyond mere excitement. This is, at present, a non-obvious goal, from a political viewpoint.

Introduction

The ideas on which physics education research was founded during the 1980s were, by and large, very consensual. It was claimed that students should actively contribute to the construction of their understanding of physics. 'Research-based teaching-learning sequences', as they were labelled later (Méheut & Psillos, 2004), were supposed to take into account students' previous ideas, knowledge and ways of reasoning in order to encourage their active involvement in learning. Indeed, and this was perhaps the most striking point of convergence, the goal was to have learners understand and learn some conceptual elements of a given targeted content.

Given the premises above, often referred to as 'constructivist', a prototypical experimental activity was supposed to make ample room for the students' intellectual activity; therefore, a question was to be solved, taking into account the learners' prior expectations. In some cases, the emphasis on this aspect was reduced, but still with a particular stress on students' engagement, via a 'problem-posing approach' (Lijnse, 1994, 1995, 2002). In any case, discussions were expected between the students and/or between the students and the teacher (or a 'mediator'), and any possible conflict between what was expected and what had been observed was supposed to be negotiated.

Some *caveats* were soon formulated by researchers in this domain. A very explicit one was enunciated by Millar: "The constructivist model of learning does not carry any necessary message about models of instruction." (Millar, 1989: p.589). Moreover, Lijnse (ibid.) rather radically claimed that a model of instruction was not sufficient to inform the design of what he thought was needed: a 'didactical structure'. Both authors insisted on the necessity of conducting a sound content analysis of the targeted content. Several books (e.g. Fensham *et al.*, 1994) also contributed to disseminating this idea. Among the other essential ideas emerging at that time was that a 'didactical structure', or any teaching-learning sequence, should be designed and evaluated at the *micro level* (Millar, 1989; Lijnse, 1994, 1995), on the basis of a fine grained analysis of the planned teaching strategies. The label 'critical detail' used later (Viennot *et al.*, 2004; Viennot & Kaminski, 2006) was just another way of underlining this idea: the devil – and not only him – is in the details. In parallel, it was acknowledged that initial views on conceptual change (Posner *et al.*, 1982) had to be reconsidered. Indeed, a 'cognitive conflict' supposedly organised by the designer of a sequence did not necessarily arise in learners, and a term-to-term substitution of ideas could not be realistically expected (e.g. Duit, 1999).

In any case, the goal was that students should gradually reach a view that was compatible with accepted physics, and/or formulate new questions. A quote by McDermott in the preamble to the booklet *Physics by Inquiry* is very explicit: "All the modules have been explicitly designed to develop scientific reasoning skills and to provide practice in relating scientific concepts, representations, and models to real world phenomena." (McDermott, 1996). A comment by this pioneer of what is now called 'inquiry-based science education' leaves no doubt: "Too often, the quality of instruction is judged on the basis of student and teacher enthusiasm; this is not a valid indicator." (McDermott, 1998). This author was not aiming *first* at students' motivation and engagement with science but at improved understanding of scientific ideas.

The present situation seems somewhat different if judged through a series of more or less official reports and loudly-stated claims about the teaching of science particularly to young and/or non-specialist audiences. For example, the Nobel laureate Georges Charpak, commenting on the movement *La Main à la Pâte*, pleaded for a strategy "… showing that, without lowering the level, we can have fun with science." (Charpak, 2005). We can also read in a report to the Nuffield Foundation that "The emphasis in science education before 14 should be on engaging students with science and scientific phenomena." (Osborne & Dillon, 2008). A report to the European Community by a group chaired by Michel Rocard, formerly Prime Minister in France, praised "… a pedagogy using an inquiry-based approach that succeeds to develop excitement about science." (Rocard, 2007: p.16). In these years of declining student numbers, numerous militant articles echo this call for excitement and engagement with science. Clearly, engagement with science is at the front of the stage, even if it is more or less explicitly assumed that a certain understanding of scientific methods, and possibly of concepts, will necessarily follow, as suggested by this type of comment: "Inquiry-based science education has proved its efficacy at both primary and secondary levels in increasing children's and students' interest and attainment levels." (Rocard, ibid.: p.3).

Given this contrast between the initial approach of physics education research, firmly orientated towards conceptual development, and a recent movement toward inquiry-based science education, at least in those versions which emphasise only excitement and interest and say almost nothing about concept learning, we might pose explicitly the following question: is there an incompatibility between an appealing presentation of physics and a recognition of its theoretical essence, as though we had cautiously to keep hidden this formal aspect? Can we hope to engage youngsters with physics whilst denying the very nature of the subject: a set of models and theories with remarkable predictive power, internal consistency and elegant parsimony, as recently underlined by Ogborn (1997, 2009)?

As acknowledged above, some pleas for inquiry-based science education may suggest, even if this is not explicitly stated, that there is an unquestionable link between these two poles. On the other hand, some authors take more extreme positions, such as Nillsen who expresses his concern about contemporary trends that he thinks neglect conceptual aspects: "If the primary objective is to make students 'feel good' about themselves, then it is unreasonable to expect them to learn very much." (Nillsen, 2009: p.5). Do we really need to see this kind of intrinsic incompatibility between pleasure and a first access to a conceptual activity?

Distancing itself from such an extreme view, this chapter will discuss the following question: given what we know from physics education research, how might we go about maximising the learning benefits of inquiry-based science education in terms of conceptual attainments, whilst keeping its motivational potential? To this end, a series of examples will be presented and discussed. They concern some simple experimental settings that typically constitute a starting point for inquiry-based science education activities in physics.

1 Discussing experts' practices

When considering an experimental setting classically used, it is worth keeping a sharp eye on some ritualistic practices. Some ways of acting, indeed, are much more often adopted than discussed, as if they were incontestable. It may happen that they go with regrettable limitations in terms of educative potential (Viennot, 2009a, 2009b). In such a case, we should go beyond being vigilant, and seek some alternatives to widen the range of benefits we can expect from them. This double approach – vigilance and reconstruction – may involve at least four components. Two of these are very classically considered in physics education research, as already mentioned: a thorough content analysis, and a sound consideration of students' common ideas and ways of reasoning. Here, two other components will also be considered. One is an analysis of experts' common practices, and the other is a search for alternatives designed in order to stress links. Indeed, as recently expressed by Kluvánek: "A person understands some information available to him or her only if he or she grasps the connections, the relationships, between phenomena, concepts and ideas to which the information refers. It can be said that the understanding of information consists precisely in the grasping of such relations." (quoted by Nillsen, 2009). This goal is consistent with that of having learners grasp a first idea of the nature of physics.

Two examples in fluid statics

The inverted glass of water

Figure 1 (A) shows a very simple experiment often associated with the role of atmospheric pressure (Viennot, 2009a). A glass full of water is covered with a piece of cardboard and turned upside down, in a vertical position. The water stays in the glass, the cardboard apparently stuck below. Students commonly say that the cardboard does not fall down because the atmosphere "supports the water's weight". This explanation makes use of two relevant forces, but it suggests a Newtonian balance between them. In fact, the upward force on the cardboard is about a hundred times as large as the weight of the water. Therefore the above explanation is, at best, very incomplete, and at worst, quite misleading.

Searching for the possible origin of this widely accepted explanation, we find several good candidates, of increasing range of application.

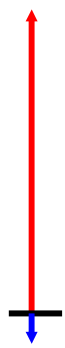
A	B	C
	Statements often found in common explanations: • The water exerts on the cardboard a force equal to its weight. • The force due to atmospheric pressure supports the cardboard which (therefore) does not fall down.	A diagram that suggests the disproportion (in fact about x100) between the values of the forces mentioned in (B): Upwards: force due to atmospheric pressure on the cardboard. Downwards: weight of the water. 

Figure 1 – A simple experiment (A) that is often 'explained' with problematic arguments (B, C).

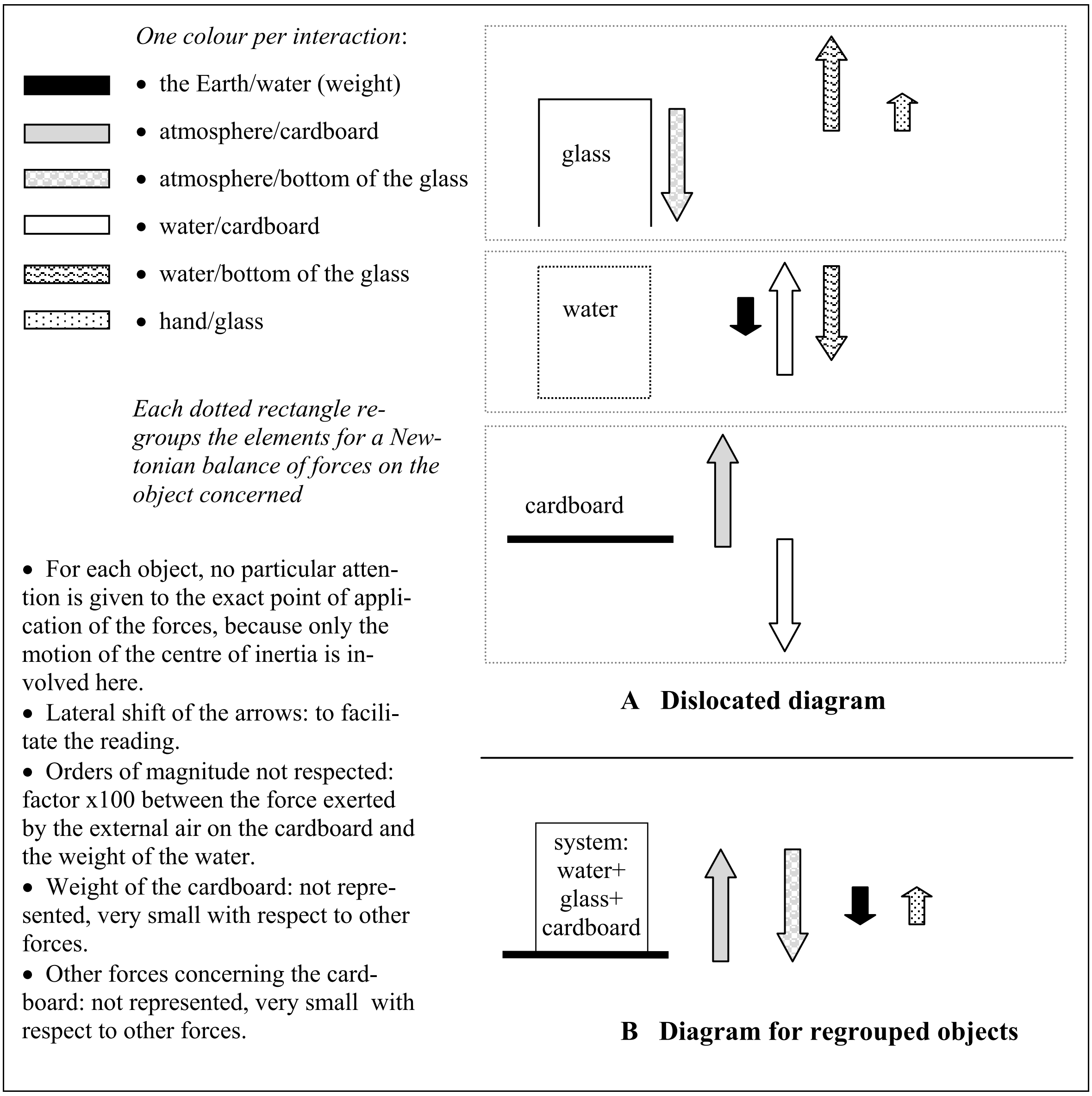


Figure 2 – Main forces (vertical components) in the situation of the glass full of water held upside down (for more detail, see Weltin, 1961; Viennot *et al.*, 2009c): (A) shows an exploded view of the water-glass-cardboard system in which the arrows indicate the interaction forces, (B) shows the balance between the various forces acting on the system water+glass+cardboard.

First, it seems as if the weight of a body, in this case the water, is thought to *always* ‘act’ on the supporting surface, in this case the cardboard. In fact, the force exerted by the water on the cardboard is of the same order of magnitude as that exerted by the atmosphere on the cardboard (Figure 2), that is, about a hundred times greater than the weight of the water.

Second, we might also argue that Newton’s third law is disregarded in this explanation. Indeed, if we were to acknowledge that the cardboard necessarily exerts on the atmosphere a force equal and opposite to the large force exerted on the cardboard by the air, it would become difficult to explain how this might happen through the effect of just a small force exerted on the cardboard by the water.

Third, this very disregard of Newton's third law might be ascribed to an 'agent-patient' scheme (Anderson, 1986) which conceals the reverse force exerted by the 'patient', namely the cardboard, on the 'agent', i.e. the outer air.

Finally, we observe that the proposed explanation is focused on the cardboard, and does not take into account the other end of the system, i.e. the upper part of the glass. It is a local viewpoint, a feature very often observed in students' ways of reasoning.

So, four hypothetical origins of this expert explanation, all compatible, coincide with some very common aspects of learner's ways of reasoning. It is in that sense that the label 'echo-explanation' is used in the following. An expert 'echo-explanation' can hypothetically be ascribed to the same features of reasoning as those commonly observed in learners and possibly misleading as regards accepted physics. This label does not imply any particular causal relationship between what is commonly claimed, respectively, by experts and by non-specialists. It just designates a mutual resonance.

The test tube full of water over a tank of water

A second example is that of a test-tube full of water, held upside-down over a tank of water, the top of the tube being 2 m above the level of the free surface of the tank (Figure 3). This situation is analogous to that of the inverted glass of water, because at the level of the free surface (i.e. at the bottom of the column of water) there is atmospheric pressure, as is the case at the level of the cardboard. As with the first example, the contact interaction between the glass and the water at the top of the tube involves large forces – corresponding here to four-fifths of the atmospheric pressure.

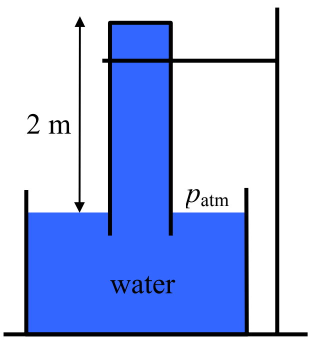
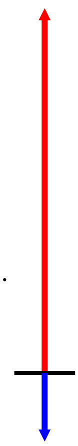
A **Test-tube filled with water, above a tank of water**	**B** **A questionable explanation**	**C** **Considering orders of magnitude**
	"What is lifting this column of water up by 2 m? It's atmospheric pressure that is pushing on the water in the tank. In the tube, there is no air, and no pressure is exerted on the water." (translated from an explanation by Marie Curie).	Comparing orders of magnitude of the forces acting on the column of water that are mentioned in the explanation (column B). 

Figure 3 – A situation that can be analysed like the glass of water turned upside down (Figures 1 and 2): a test-tube full of water and turned upside down over a tank filled with water.

An expert explanation for this phenomenon was provided by Marie Curie. A book recently published presents notes taken by Isabelle Chavannes during lessons given in 1907 by Marie Curie to a few of her friends' children (including Isabelle). Referring to the setting shown in Figure 3, Isabelle Chavannes reported Marie Curie's words: "What is raising this column of water up to 2 m? It's the atmospheric pressure that is pushing on the water in the tank. In the tube, there is no air, and no pressure is exerted on the water." (Chavannes, 1907).

With this comment, we are very close to the common and problematic explanation of the inverted glass discussed above. A column of water is said to be raised by atmospheric pressure (the active agent?), and this suggests an (unbalanced) equilibrium between two forces, given that it is (erroneously) claimed that there is nothing else acting on the water at the top of the column of liquid. This expert explanation echoes, term for term, the explanation of ordinary learners.

Suggesting alternatives

Once a common practice is analysed and some interpretative hypotheses are proposed, it is possible to design some different – complementary – ways of staging the simple device concerned. In the case of our first example, this can be done by changing the physical situation slightly. In order to avoid reinforcing the idea that the atmosphere is playing the role of a stand 'supporting' the weight of the water, we can put the glass horizontally (Figure 4).

Figure 4 – Also in a horizontal position, the water does not flow out of the glass.

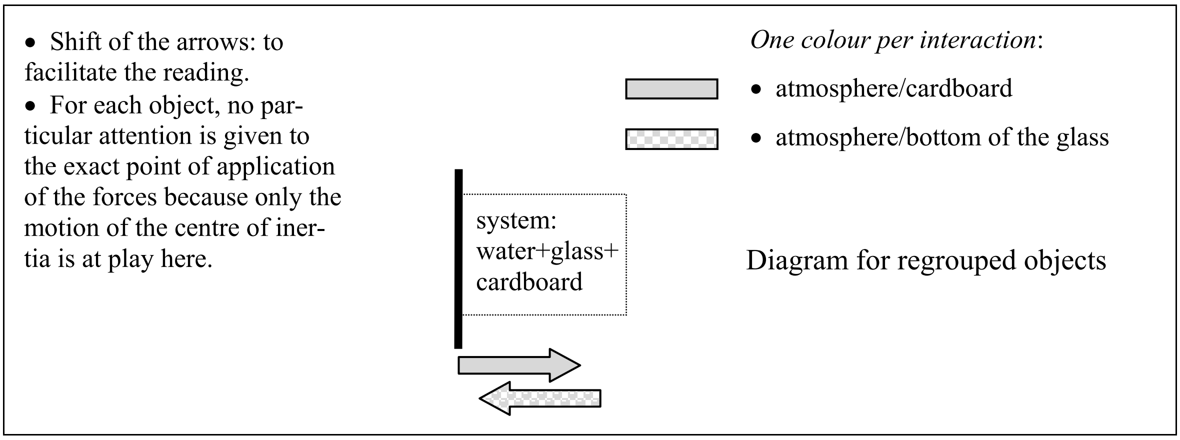


Figure 5 – Main forces (horizontal components) acting on the glass of water in a horizontal position.

Then, a simple analysis of the horizontal components of the main forces (Figure 5) leads to a more symmetrical view, which is systemic and involves both ends of the glass. The atmosphere appears as playing the role of a press rather than that of a stand. It is likely that the learning outcomes would be different, or at least that the conceptual obstacles would not be the same.

The second example does not lend itself to that kind of change, as the test tube cannot be put horizontally. But it is still very relevant to focus on the systemic aspect. As in the case of the inverted glass, both ends of the column of water deserve attention. Indeed, at the top of this column, the interaction between the water and the glass is equivalent to that generated by four fifths of atmospheric pressure. Stressing the links between the two situations, inverted glass or test tube, is likely to lead to a better understanding of this idea. It is even possible to discuss what a Torricelli barometer is, and to underline that there is a very small interaction, in this case, between mercury vapour and the top of the tube (about 0.2 Pa). By stressing similarities and differences, via a systemic analysis, an investigation of an inverted glass, an inverted test tube and a barometer gives access to a rich and consistent conceptual content.

Similarities and differences: going further with familiar experiments about fields

The next example illustrates a particularly big gap between a targeted conceptual content and the relatively simple messages conveyed – at first sight – by the experimental facts in play. It is commonplace to use iron filings in order to show the action of a magnet in the surrounding space. Faraday (1852) called the lines that can be drawn at a tangent to these iron filings “lines of force”, and advised us “... to consider magnetic power as represented by lines of force”, given that “the lines of force, well represent the ‘nature’, ‘condition’, ‘direction’, and ‘amount’ of the magnetic forces.”

A first way to widen the conceptual content related to this kind of experiment is to demonstrate its three-dimensional aspect, using a device like that shown in Figure 6. In a teaching-learning sequence tested experimentally at grade 4 and 5 levels (Bradamante & Viennot, 2007), this is just a first step. This sequence was designed to stress the similarities and differences between gravitational and magnetic fields. Although this target may seem excessively ambitious for children aged 10-11, it was considered worth investigating, in particular because it is well known that pupils tend to ascribe the Earth’s gravitational action to the fact that this planet is a magnet (e.g. Arnold *et al.*, 1995; Bar *et al.*, 1994; Nussbaum, 1985).

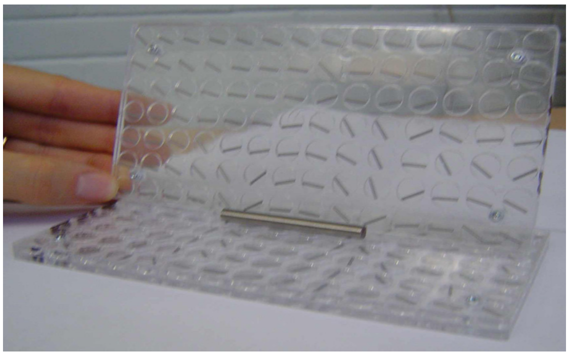


Figure 6 – Demonstrating the 3D influence of a magnet.

The authors of the teaching-learning sequence hypothesised that, for children, geometrical aspects were very salient (Saltiel & Malgrange, 1980) and, hence, that what we prefer to call ‘field lines’ might be an appropriate entry point for comparing gravitational and magnetic fields. The idea of ‘mapping’ the influence of the Earth and of a magnet in the region surrounding them was central to the sequence. Figure 7 shows how a child in grade 5 represented some gravitational detectors – in fact, balloons attached to a tree by a string, or pendulums – all around the Earth.

This idea of mapping, introduced by the designers of the teaching-learning sequence, was seemingly well accepted, and some pupils were subsequently able to produce some drawings like in Figure 8, and to compare the ‘maps’ representing the influence of each object.

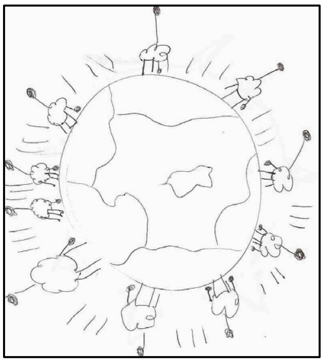


Figure 7 – Drawing by a child aged 11, showing the positions of pendulums and balloons attached to a tree, around the Earth.

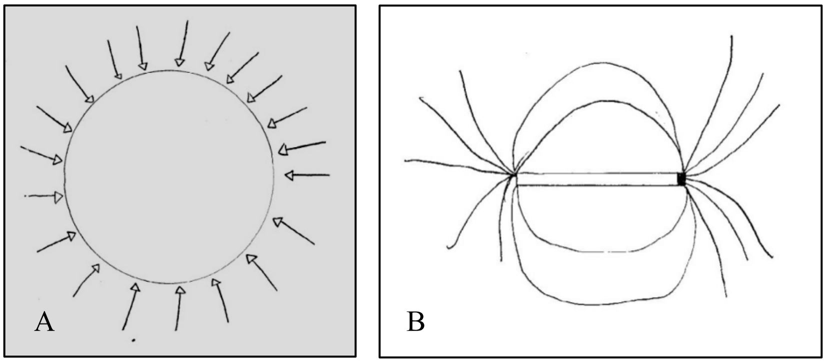


Figure 8 – Drawings by a child aged 11 to compare the ‘maps’ corresponding to the Earth (A) and to a magnet (B).

But it was also observed, particularly in the final test (Figure 9), that a different mapping for the Earth and for a magnet was not enough to have the children fully accept that the two phenomena were really different. Despite the recognition that the maps were different, some children also claimed that there was a similarity, and drew some lines heading for the centre of each of the objects considered, with comments like: “It heads for the Earth.” (11 years old).

Are there any similarities?
Yes
If so, which one(s)?
Explain: *It heads for the Earth.*

Are there any differences?
Yes
If so, which one(s)?
Explain:

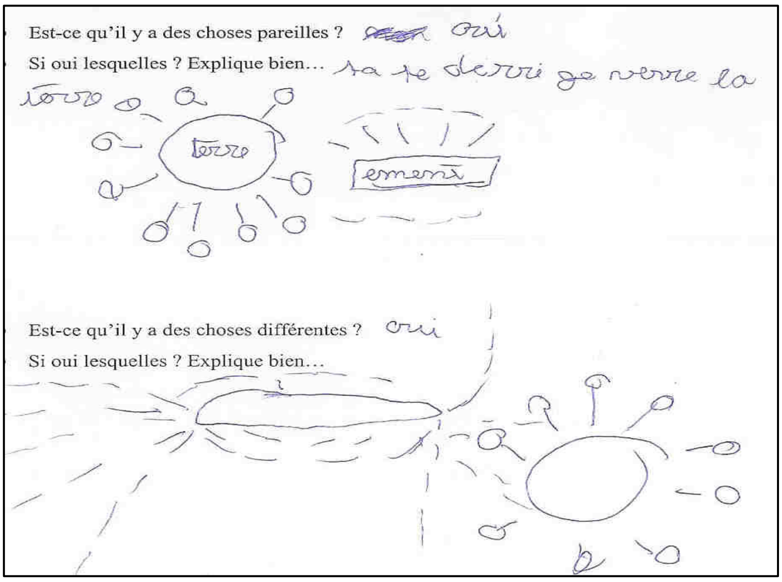


Figure 9 – Comparing the influence of the Earth and of a magnet: response of a child aged 11 in the final test.

This final state of affairs echoes some responses given earlier in the course of the teaching-learning sequence, when children were asked to predict the position of a small compass placed on a map of field lines drawn around a magnet. Table 1 shows that a noticeable proportion of pupils, in the two age groups, drew the compass needle pointing towards the centre of the magnet. Clearly, the idea of mere attraction remained prevalent among these pupils.

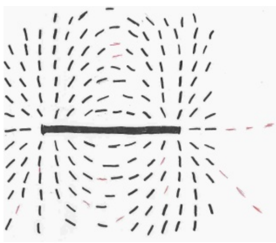
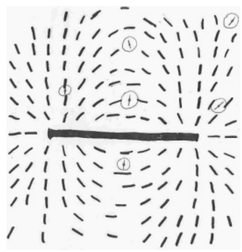
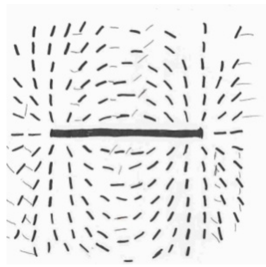
	Correct	Mixed Correct near the ends of the magnet, toward the 'middle' on the transverse plane of symmetry	Mixed (other) Correct near the ends of the magnet, some 'erect' needles elsewhere
			
G_1 N_1=17	4	4	9
G_2 N_2=16	7	5	4

Table 1 – Interpolation of magnetic interaction: drawings of compass needles near a magnet by children in grade 4 (aged 10, G_1) and 5 (aged 11, G_2).

This investigation thus underlined some facts that may remain disregarded in a more ritualistic introduction of magnetism. For instance, it is common to say that a magnet attracts ferromagnetic materials, and attracts or repels other magnets. Such statements, although correct, do not facilitate the comprehension of the fact that two phenomena may occur at the same time: global attraction (or repulsion) *and* orientation (Figure 10).

Moreover, what is directly linked to Faraday's "lines of force" – now called 'field lines' – is not a force, but rather the orientation taken by a magnetic dipole placed on the line. It seems appropriate to stress that these lines are really 'lines of orientation'.

In brief, with this sequence, we have an example of considerable conceptual added value for a very modest and commonplace experimental starting point: iron filings oriented by a magnet and a thought experiment with pendulums around the Earth. A preliminary condition for such a conceptual ambition is to distance oneself somewhat from comments that ritualistically accompany some simple experiments and directly echo what a child would spontaneously say.

Here, a very specific spotlighting of the content, i.e. the central role of mapping, made it possible to analyse similarities and differences between two fields, thus pinpointing, ultimately, the distinction between unipolar (central) and dipolar fields.

Stressing links, or equivalently differences, widens the conceptual space that is potentially accessible on the basis of a simply experiment, provided that the limits of some common practices are recognised and analysed.

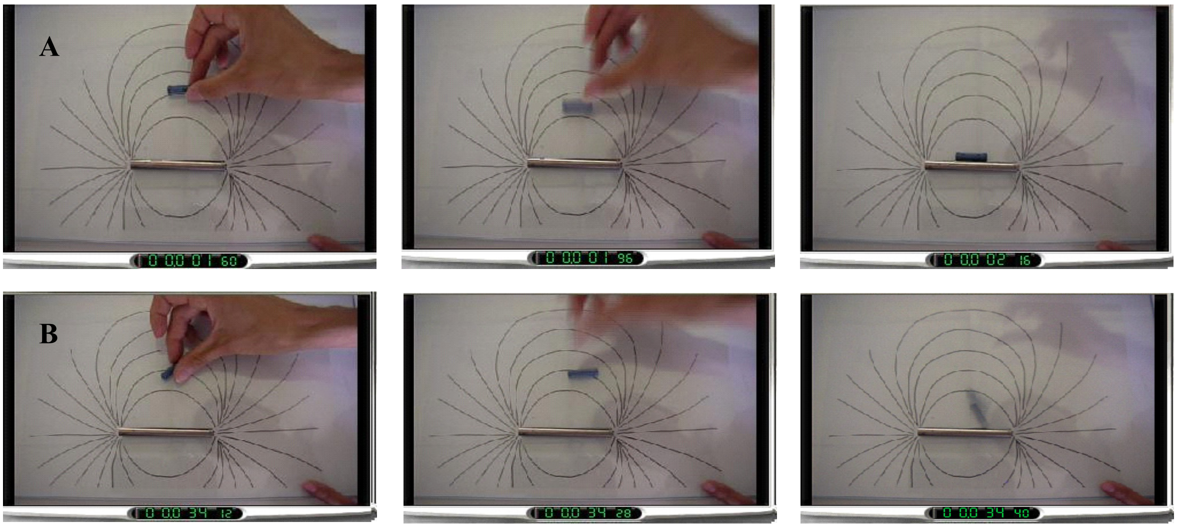


Figure 10 – Two situations of interaction between two magnets: global attraction without rotation (A), simultaneous evidence of attraction and orientation (B). Video: F. Bradamante.

The two last examples are intended to buttress once more this idea. In order to better understand their relationship with the idea of echo-explanation, it is necessary to bear in mind the main features of a common way of thinking in science: linear causal reasoning.

2 Linear causal reasoning

Linear causal reasoning is of particular interest in that it is in stark contrast with some models commonly used in accepted physics, and particularly in elementary physics.

Consider a system comprising several objects, say two springs suspended end to end from a stand and extended by an experimenter (Figure 11), or a series circuit with two resistors and a battery, or two cylindrical vessels filled with gas and separated by a mobile piston. Such systems can be described with several variables that are constrained by simple relationships. Thus, the forces exerted by the two springs on each other are equal to the force exerted by the experimenter on the lower end of the lower spring. This relationship implies a situation of mechanical equilibrium at every point in time, the same time argument being ascribed to every specific value of the quantities concerned. In other words, all the parts of the combined system are assumed to ‘know’ all the other parts *instantaneously*, during the – *quasi-static* – evolution of this system. Thus, if the lower end is pulled by an experimenter, the relationship above is assumed to hold at any instant. This is far from obvious. In the case of an earthquake, for instance, this model would not be appropriate for analysing the changes that affect two contiguous parts of a continent. It would have to be changed to a *propagative* model. In passing, we note that it is more common to discuss the relevance of a quasi-static model in thermodynamics than in mechanics.

The simultaneous evolution of all the parts of a system is far from intuitively clear. Common ways to deny such a strange hypothesis take the form of the following prototypical comment (Fauconnet, 1981: p.111; Viennot, 2001: p.98): “The first spring will extend. Then, after a while, the second will also extend.” Such a comment suggests that the event is seen as ‘a story’, rather than as simultaneous changes in several variables permanently constrained by the same relationships. Simple events (φ_n), most often specified through only one variable, are envisaged as a series of binary cause-effect links: $\varphi_1 \rightarrow \varphi_2 \rightarrow \varphi_3 \rightarrow (\ldots) \rightarrow \varphi_n$ (Rozier & Viennot, 1991; Viennot, 2001: chap.5). The arrow used in the preceding symbolic form is often expressed in words using the adverb ‘then’. This is an intermediate term between the expression of a logical link (‘therefore’) and a temporal succession (‘later’). We can find the same type of ambiguous term in many other languages as well; for instance ‘alors’ in French or ‘entonces’ in Spanish. More or less surreptitiously, common explanations are steeped in time.

Figure 11 outlines the term-to-term opposition that exists between the linear common reasoning and a quasi-static, or quasi-stationary, analysis of a systemic change. Not only do these two different approaches differ in their wording, the corresponding solutions for a given question are also different. For instance, the lengthening of the upper spring for a given total extension can be found to be too large by a student who proceeds as follows: first consider the extension of the lower spring as equal to the displacement of the lower point, then calculate the corresponding force, then apply this force to the upper spring, then calculate the corresponding extension.

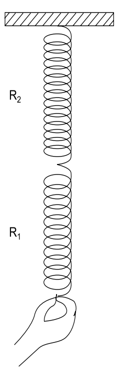
In quasi-static physics	Example	**Linear causal stories**
• several variables • simultaneously changing • constrained by permanent relationships		• simple phenomena (one variable each) • seen as successive (hence as) • temporary
$\boldsymbol{F}_{ext}(t) = \boldsymbol{T}_1$ (same t) $= \boldsymbol{T}_2$ (same t) $\Delta l_T(t) = \Delta l_1$ (same t) $+ \Delta l_2$ (same t) $\boldsymbol{F}_{ext}$: Force exerted by an experimenter on the lower end; $\boldsymbol{T}_1$, $\boldsymbol{T}_2$: tensions of each spring; Δl_1, Δl_2: extensions of each spring; Δl_T: total extension.		*A symptomatic comment:* “The first spring will extend. Then, after a while, the second will also extend.”

Figure 11 – The main features of linear causal reasoning, compared to those of a quasi-static analysis.

Expert explanations that echo linear causal reasoning

As already pinpointed by Rozier and Viennot (1991, see also Viennot, 2001: chap.5), some expert explanations seem also to be framed by linear causal reasoning, a tendency that can be particularly perpetrated by authors of science popularisations. The following example, in line with the theme of this paper, is about a simple experiment: a siphoning process (Figure 12).

An explanation, again given by Marie Curie (Chavannes, 1907: p.62), makes use of the following argument: “The water in the long branch of the siphon flows out. A vacuum is created, and the atmospheric pressure pushes the water of the tank up the short branch.”

Using the schematic presentation above, we might paraphrase this explanation as follows: φ_1 (left end of the tube in Figure 12): the water in the long branch of the siphon flows out $\rightarrow$ φ_2 (somewhere in the tube): a vacuum is created $\rightarrow$ φ_3 (right end of the tube in Figure 12): the atmospheric pressure pushes the water in the tank up the small branch.

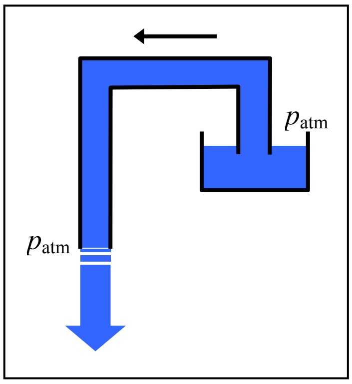


Figure 12 – A siphoning process.

Simple events are envisaged successively, if only temporarily (for instance: ‘the vacuum’), as though in chronological succession. In particular, this would seem to suggest that it is possible to analyse what happens at one end of the system independently of what happens at the other.

There is one clear problem: The role of the atmosphere is called on for the last link of the explanation, which concerns one end, but there is atmospheric pressure at the other end as well.

The adjectives ‘long’ and ‘short’ constitute a clue which discretely points towards the crucial role of a difference. Most probably, this clue is not sufficient for learners who do not already know how to analyse this system. It might well be thought, for instance, that the water flows out of ‘the long pipe’ simply because its lower end is open. The resonance between this explanation and linear causal reasoning, clearly, may result in improper interpretations.

3 Stressing links … and the decisive role of some differences

Analysing the possible risks associated with a simple experiment is an encouragement to choose its main teaching goal more explicitly. Thus, still using the same device, it may be decided to stress the systemic aspect of a siphon. To this end, the students can be first presented with a system analogous to that shown in Figure 12, but with a mask hiding the right-hand side (Figure 13a). The student could be asked to predict: what would happen if the lower end of the left-hand branch, initially blocked, were freed? Once performed, the experiment would confirm what is commonly expected: the water in the left-hand branch flows out. When the mask is taken off (Figure 13b), the students can see that the vessel empties, which is the usual goal of a siphoning process. But the experiment could also be performed for a different outcome. Behind the mask, and with exactly the same visible part on the left, it is possible to place the tank of water such that its free surface is *lower* than the end of the left-hand branch (Figure 13c). Then, when the left-hand end of the tube is opened, the water does not flow out. Instead, the water rises up the tube and refills the tank.

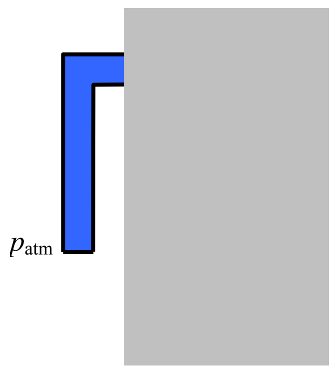
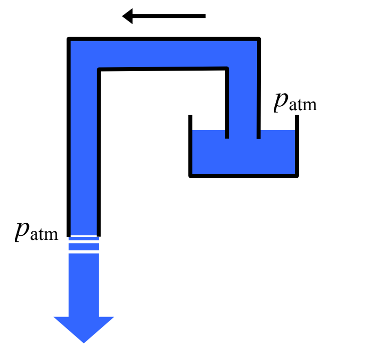
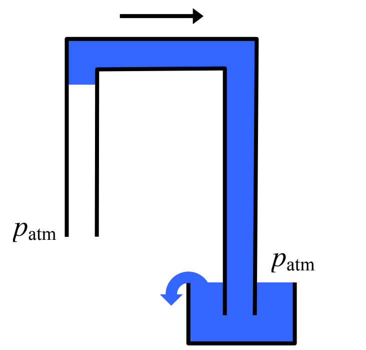
A	B	C
		
What will happen when the left-hand branch is opened at its lower end? (Right-hand part of the system: hidden.)	A case currently explained by experts (e.g. Marie Curie: Chavannes, 1907)	With the same left-hand branch, a different outcome is observed.

Figure 13 – Without considering both sides of a siphon, the outcome of the experiment cannot be predicted.

This is a striking illustration that, without seeing *both* ends of the system, it is impossible to predict what the water will do. This is the most important thing to be understood concerning a siphon. Beyond that, with a modest setting, and with an audience that is still at a low level of competence, it is possible to stress a crucial aspect of physical phenomena: the world runs on *differences* (Boohan & Ogborn, 1997).

Keeping in mind this kind of a message – briefly put, the relevance of a systemic approach – the staging of other experiments can be re-orientated accordingly, as illustrated by the following example.

A ‘love-meter’ is shown in Figure 14. Warming up the lower part with the hands results in a nice fountain effect, with the liquid partly filling in the upper part whilst its level decreases in the lower part. The usual explanation is that warming up the gas in the lower part increases the pressure there, which pushes the liquid up the tube joining the bottom of the lower part to the bottom of the upper part. Here, we recognise linear causal reasoning.

In order to highlight the target idea more effectively, we could formulate the explanation more precisely, changing ‘the pressure increases in the lower part’ to ‘the *difference* of pressure between the *two* parts is increased’, thus taking into account both parts of the system. With such a target in mind, it would become natural to complete the classical demonstration of the love-meter experiment with the following variation (Figure 15b): cooling down the upper bulb, for instance with cold water. The outcome is of course the same as with the usual version, which constitutes a rather striking effect.

Figure 14 – A ‘love-meter’ with the classical staging.

Figure 15 – A staging of the demonstration that focuses on a systemic analysis: starting with the classical use of a love-meter (A) …then cooling down the upper bulb with cold water (B).

Among other activities, these two examples – siphon and love-meter – could be used to emphasise the consistency of physics and the power of its theoretical foundations: in this case the idea that the world runs on differences.

Final remarks

This chapter is centred on the topic of simple experiments. This theme, in fact, served as a particular basis to illustrate more general ideas. The first – a condition for the relevance of the others – is that even with severe teaching constraints, there are some open choices and levers for targeted actions. Some apparently minor changes in ritualistic practices may bring out important outcomes. These ‘critical details’ of practice, when orientated by a sound analysis of the content and a sufficient knowledge of students’ common ideas and ways of reasoning, open up a range of different targets. Being vigilant about our own explanations, which may in fact mirror some problematic features of common reasoning, is a preliminary condition. Among the possible goals that might influence what we choose to spotlight in exploring any given content is that of stressing conceptual links, thus highlighting how consistent, predictive and concise physical theories may be, in specified domains of validity.

A few questions might be posed in this respect, some of them rather pragmatic. First, are suggestions of the kind made in this chapter realistic, or is it inspired by an elitist perspective? In terms of cost in time and money, the examples outlined in this chapter provide a clear answer. It is not more expensive to put a glass of water in a horizontal position than in a vertical one; pouring some cold water on top of a love-meter is not much more complicated than warming up its lower bulb. Similarly, staging the siphon as suggested is by no means a difficult enterprise.

This said, the fit between the audience and the complexity of the targeted concepts is, of course, to be discussed and iteratively evaluated and adjusted. This is typically what physics education research has, over a long period, been engaged in doing. For example, as discussed above, the attempt to link the gravitational and magnetic interactions structurally to some geometrical features – the corresponding field lines – is probably better adapted to students slightly older than those involved in the experimentation outlined above.

As regards teachers, a crucial question is: how can they appropriate ideas and suggestions of the kind advocated here? This question is a recurrent one which concerns any innovation. The STTIS project (Pinto *et al.*, 2001) for instance, or the Leeds group (Leach & Scott, 2002, 2003), among others, have underlined how complex this question may be and searched for ways to deal with it. The mere dissemination of descriptions of 'good practices', despite its obvious attractions, is probably insufficient. The very notion of a 'good practice' *per se* is questionable, as the particular history and context of a class may strongly determine the choices that are *a priori* the most appropriate.

It might be more profitable for teachers to be provided with some means of consciously reflecting on and making their own choices. For a given well-specified spotlighting of a content, a material setting and a particular staging can be suggested, along with the reasons for using them. Possible links – between concepts and/or between phenomena – can be suggested, and again well justified. Ideally, variants might be proposed that may focus on such and such an aspect of a phenomenon, this focus resulting from the factors that are to be made explicit.

This suggestion is in line with a view of teacher training previously advocated. Viennot *et al.* (2004) argue that "What should be aimed at in such training, we think, is an ability to link *any* global rationale to precise details of practice." In such a 'problem-posing approach' (Lijnse, 1994, 1995), the target is to maximise didactical consistency between a global view on what students should understand and some particular teaching strategies. Although illustrated here at small scale, i.e. with simple experiments, the teachers' productions in such a training programme, or the suggestions made to improve science teaching (see for instance *MUSE*: Planinsic *et al.*, 2009), could be described, in Lijnse's words, as "well-motivated possible routes to solutions of didactical problems" (Lijnse, 2000: 323).

At least we can say that it is not advisable to overrate a particular 'method' in itself, and still less, the merits of surprising experiments, if they dispense with these necessities: a critical distance as regards teaching rituals, a serious consideration of the consistency of physics and of students' views, and a thorough discussion of the specific way of spotlighting the taught content that is adopted. All are necessities that have been, to the utmost, stressed by Piet Lijnse.

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3

Using research to improve practice in science education: Where should we begin, and what should we aim to produce?

Abstract

Many science educators would agree with Lijnse (2000) that their interest is in "research that can, and does, improve the practice of teaching and learning physics." (p.308). The claim that research can contribute significantly to the improvement of practice, however, makes some assumptions about the nature of educational knowledge and its relationship to professional practice. And the aspiration to *improve* the practice of teaching and learning physics (or science more widely) implies that there is a reasonable level of agreement about how to recognise improvement of outcome or process – in other words that publicly agreed measures of quality exist. I want to explore the implications of these assumptions for the design and dissemination of teaching activities and lesson sequences that aim for improvement in students' learning.

I will argue that, to improve practice in the teaching of X (where X is any given science idea or topic), we need to shift the focus from teaching to learning, and start from the question of how we will recognise the learning outcomes we desire. And that we should see the development of detailed teaching sequences as a means of establishing 'proof of principle' – of demonstrating that an idea we have about how to teach X can be operationalised in a form that teachers consider feasible to implement. The product is therefore better seen as a template, or framework, to guide and influence teachers' actions in the classroom rather than as a blueprint to be enacted.

Introduction

> "… my interest in the field of physics education research is of a rather practical and pragmatic nature. I am not interested in research on understanding teaching and learning as an aim in itself, even if the teaching and learning concerns physics. What I am interested in is research that can, and does, improve the practice of teaching and learning physics." (Lijnse, 2000: p.308)

> "… developmental research deals essentially with questions like 'how to teach X' or 'how to teach X better'." (Lijnse, 2003: p.12)

What is the point of research in science education? In the first quotation above, Piet Lijnse makes clear his personal answer to that question: its central purpose is to improve the practice of teaching and learning science. He does not claim that improving practice is the only purpose of science education research, just that it is what he is interested in. Many science educators would agree – that they are interested in 'research that can, and does, improve the practice of teaching and learning' science. The desire to improve the teaching and learning of science (or of one of the sciences) is what brought many of us into science education research. Practical improvement is also what teachers, policy-makers and those who sponsor research want and expect of research. There are, however, few examples of research-informed guidance on science teaching that are widely followed and have had a noticeable impact on the practice of many teachers, or on the learning of their students.

Lijnse (2000) argues that an appreciation of the importance of content is the ‘forgotten dimension’ in science education research – and a major reason for its lack of impact on practice. He describes his own disappointment, early in his career, at discovering that theories of education and educational psychology offered him almost no help in developing a series of lessons to introduce quantum mechanics at secondary school. He argues that content-independent theories of learning, or teaching, or curriculum, or classroom organisation, provide little useful guidance to a teacher preparing to teach a given science topic – preparing to teach X. The implications of a general theory for teaching any specific body of content are unclear; the task of trying to work out these implications is substantial – and would need to take proper account of the nature and structure of the particular content to be taught. The aim of ‘developmental research’ (Lijnse, 1995) is to produce domain-specific research-based guidance, in a form that can directly influence practice.

I share Lijnse’s dissatisfaction with the outcomes of research on the teaching and learning of science topics. Given the huge amount of research that has been carried out, and the amount that has been written and published, it is surely reasonable to expect this to have resulted in some clear and reasonably specific guidance that could be given to teachers, based on knowledge that is warranted (at least to some extent) by research rather than only by professional experience and judgment, about how to teach more effectively the things they have to teach. It is not at all clear that it has. Research-based guidance is unavailable not only on the teaching of unusual topics like quantum mechanics; even for topics where a large amount of research has been carried out and reported, such as electric circuits, Newtonian mechanics, and the particulate model of matter, there is little evidence of its systematic impact on teaching materials (such as textbooks) or on the practices of most teachers. If research on the teaching and learning of science topics is to have a significant impact on practice, it must provide teachers with guidance that is practically useful, on teaching the things they have to teach – on teaching Xs.

I want to explore briefly three issues that this agenda raises. First, I will ask if it is reasonable to expect research to influence educational practice in this very direct way. I will conclude that it is, but with some caveats about the form that such guidance can take and the claims it can make. Second, I will argue that there is another ‘forgotten dimension’ that undermines efforts to disseminate research-based guidance on teaching X, namely the instruments and methods used to obtain evidence of learning. Third, and influenced by the discussion of the first two, I want to discuss the form that research-informed guidance on how to teach X might take, and how we should regard it.

1 The relationship of research and practice in education

The view that research can and should provide answers to questions like ‘how to teach X’ or ‘how to teach X better’ is central to the notion of ‘evidence-based practice’ in education (Institute for Effective Education, 2009; Institute of Education Sciences, n.d.). Over the past decade, there has been a wave of advocacy, principally in the UK and the US, of forms of educational research that can provide evidence to inform and guide the decisions and choices of practitioners and policy-makers (Hargreaves, 1996; Fitz-Gibbon, 2000; Torgerson & Torgerson, 2001; Slavin, 2002; US Department of Education, 2002). These authors (and others) have argued that educational research should be modelled on the form of research that is widely seen to have transformed the effectiveness of medical practices over the past century, in particular experimental trials, ideally with randomised allocation to experimental and control groups. These, too, focus on improving the ‘treatment of X’, not on identifying general, illness-independent practices.

This kind of vision of a ‘science of education’ is not new. It has a lengthy history, dating back at least to the 19^{th} century (Bain, 1879), but has never really taken hold as the dominant research paradigm. A significant reason for this is that it has not delivered the kind of evidence, or had the impact on practice, that its advocates promised. Critics of the idea of ‘evidence-based education’ argue that it is based on a mistaken view of education, and of the relationship between educational research and practice. Hammersley (2002), for example, argues against an ‘engineering’ model of the relationship between research and practice “which views research as providing specific and immediately applicable technical solutions to problems” (p.38). Rather, he suggests, “the usual, and perhaps the most appropriate, way in which research shapes practice is through ‘enlightenment’: through providing knowledge or ideas that influence the ways in which policymakers and practitioners think about their work” (p.38). He bases his argument on the fact that educational practices are fundamentally grounded in values, about what is worth teaching and learning, and about the teaching and learning transaction, which cannot be determined by technical information or empirical evidence, and on the view that research cannot supply all of the knowledge needed by practitioners, some of which is locally specific.

Both of these points are important. In science, as in every subject, choices about what to teach, what approach to take to a topic, which aspects to emphasise, the depth of treatment, and so on, are value-laden. They are influenced by our views on why we are teaching science to any particular group of learners, what teaching and learning science means, and why certain learning outcomes are worthwhile. Clearly research can only claim to say something about ‘how to teach X’, not about ‘whether to teach X’. Even were we to find an outstandingly successful way of teaching X, that would not of itself provide any evidence that we *ought* to be teaching X to any particular group of learners. The decision to teach X, and the interpretation of what ‘teaching X’ means, embody values. When developing a research-informed teaching intervention, we should, perhaps, make explicit what these underlying values are, and how they inform its design – and contrast these with the values implicit in current practices.[1] These issues of value have a bearing on the adoption of guidance on how to teach X. We should anticipate, and accept, that any particular example of research-informed guidance on 'how to teach X' will not be adopted by some teachers (and also by some researchers), even if there seems to be quite clear evidence in favour of doing so, because they do not share the values implicit in that guidance.[2]

Similarly, the argument that actions and decisions in the classroom draw not only on general context-independent knowledge but also on locally specific knowledge has significant implications. Anyone who has ever taught the same topic twice to two different classes knows that it is not the same on both occasions – and that the differences may be considerable. This is not a flaw in their practice; rather it is how things ought to be. Good teachers plan their lessons in the light of their knowledge of the class and the individual students in it, and of the teaching context. Good teaching is also responsive 'in real time' to the learners – and the response of two different classes to the same teaching is never the same.

Consequently, anything we say about 'how to teach X' must be qualified, and probabilistic. The way a teacher teaches may suit some students in a class, but not others. I was taught mathematics, for example, in upper secondary school by a teacher who was (for me) an excellent teacher, but who was not such a good teacher for some in the class who found mathematics more difficult than I did. So 'how to teach X' may be different for different learners in a class. Also teachers themselves have different skills and capabilities. Some know that they cannot handle some kinds of teaching well. So the best way to teach X may be different for different teachers. The best we can hope to do is to recommend 'how to teach X' to certain types of learner, in specified contexts, in a way that is likely to optimise (but in no way guarantees) the intended learning outcomes.

These issues and their implications underpin the unease of Hammersley (2002, 2007) and others about an interpretation of 'evidence-based practice' as the provision of detailed research-based guidance and materials that teachers can adopt and use. Gunstone and White (2002) also question this view of the research-practice relationship, arguing that:

> "The way research influences practice in education is not through discovery of a detailed and specific mode of teaching but through substantiation of principles that pervade thinking about teaching and learning." (p.302)

They do not, however, go on to discuss what 'substantiation of principles' might mean, or indeed how the 'principles' that might apply to the teaching of any specific content could be identified.

Despite these issues, and unlike Hammersley (2002), I find the 'engineering' model useful for thinking about the relationship between science education research, the development of teaching materials and programmes, and classroom practices (Campbell *et al.*, 1994). The starting point is a perceived problem in cur-

[1] Which are rarely acknowledged or discussed.

[2] I do not mean to imply that this will be their explicitly given reason, but that it is, in effect, the grounds for indifference or rejection.

rent practice. Drawing on knowledge of different kinds, including research, we construct an artefact – a teaching sequence or some other form of guidance – which we think will improve the situation. It may succeed, if it is seen by those working in the situation as an improvement. And it can be evaluated against criteria related to the original problem that led to its development. The issues discussed above, however, suggest that we ought to reflect on the kind of artefact we should try to construct, if our aim is to influence the practices of many teachers for the better.

2 Assessment of learning outcomes: The forgotten dimension in science education research

Lijnse, in the first quotation at the head of this chapter, says that his interest is in "research that can, and does, improve the practice of teaching and learning physics" (2000: p.308). Of course we seek to improve, not merely to change. But can research lead to improvement, or are changes in practice simply responses to changing external circumstances, changing demands, changing fashions, and so on? How might we justify the claim that a particular example of research-based guidance on 'how to teach X' leads to an *improvement* in practice?

The most obvious answer to this – and I think the one that most sponsors of research and also many teachers expect – is that it results in a measurable improvement in students' learning as compared with other ways of teaching X. The advocates of evidence-based education argue that the best evidence that a teaching intervention 'works' is obtained through an experimental trial, comparing a 'treatment group' with a 'control group', with individual students or classes allocated randomly to each. This assumes, however, that robust and generally-accepted measures of learning outcome are available.[3] Unfortunately they are not.

The 'detection', or measurement, of desired learning outcomes is critically important for much of the work that goes on in science education, but has been seriously neglected. A central problem is that many educational outcomes are not directly observable. We say we want to teach 'for understanding' – but how do we know if a student 'understands' a specific idea or does not?[4] Mulhall *et al*. (2001) highlight the same issue when they ask, "what, in detail, do we expect students to learn when we talk of 'conceptual understanding' in electricity?" (p.583). They argue that "we [the science education community] do not have even the beginnings of systemic answers" (ibid.). They go on to say – and I would agree – that "some justified response to [this question] is a necessary, if not sufficient, condition for any helpful advances in the thinking about and practice of teaching electricity" (ibid.). The problem does not apply only to electricity.

As we cannot observe understanding directly, we must infer it from things we *can* observe: what the student says, or writes, or does, usually in response to a given

[3] The advocates of randomised trials in education often seem rather blind to this requirement.
[4] Or, if we prefer not to think of 'understanding' as a dichotomous variable, how do we describe or characterise their 'level of understanding'?

stimulus (such as a question, or task). In other words, we must 'operationalise' the objective: 'understands Y' becomes 'is able to make the desired response to a given question or task involving Y'. Through this process of operationalising objectives, we become much clearer about what our objectives really are, and what they mean. We also communicate these objectives much more clearly to others. And we put tools for collecting evidence of learning into the public domain, where they can be discussed, criticised, and improved. This kind of work strongly involves subject-specific didactical knowledge.

All of this becomes even more acutely important if our learning objectives are broader and more diverse than understanding canonical science content. If, say, we want to develop students' ability to construct a sound argument based on evidence, or to de-construct an argument put forward by someone else, how do we identify those students who can do this in the way that we wish, and those who cannot? Or if we say we want to improve students' understanding of some aspect of scientific enquiry, or of scientific reasoning, or of the nature of science, how do we know if a student has learned what we wanted him or her to learn, or has not? Only by operationalising these learning outcomes – by developing tasks and instruments that might provide evidence of students' understanding or capability – do we ourselves come to an understanding of what we had in mind, of what it really is that we want students to learn.[5] I should make clear that I am not arguing that all we need are more short, sharp inventories of multiple-choice questions like the Force Concept Inventory (Hestenes *et al*., 1992), though these have a role to play. Our learning objectives may be much broader. We may, for example, want to improve students' ability to take part in well-informed discussion about a science topic – and see this as a better measure of their understanding than the ability to answer some written questions. Fine – but then we need to specify in some detail how we will recognise those students who can display the intended learning – what the observable characteristics of their contributions to discussion will be. The same would apply if we said our objectives were largely, or partly, in the affective domain – to improve students' interest in a science topic or encourage a more positive attitude towards it. We need to ask: how will we recognise the outcome(s) we desire?

The central point I want to make, then, is that efforts to develop research-informed teaching interventions in science have focussed too strongly on teaching, and not sufficiently on learning. More effort has gone into trying to change what teachers do in the classroom, than into trying to measure what learners can do as a result of the teaching. A mature research community is characterised by several things, including some measure of agreement about good questions to ask, and about appropriate tools and methods to use to try to answer them. On this criterion, the field of science education research has not yet reached maturity. We need, as a community of science educators, to put more effort into developing better and more publicly-agreed measures of the learning outcomes we desire. This will make it more possible to provide the kind of evidence that might persuade others to adopt a

[5] Or perhaps discover that what we said we wanted them to learn really doesn't make much sense, and we should drop the idea.

new way of teaching X. It will also help *us* to understand better what our objectives really are.

An appreciation of the critical role of assessment in specifying learning outcomes, and hence in shaping instruction has led Wiggins and McTighe (2006) to develop the idea of 'backward design' of instruction. They argue that the development of a teaching intervention should *start* from the tasks and exercises that will be used to identify successful learning outcomes, and then work backwards from this towards a sequence of teaching and learning activities. One strand of the *Evidence-Based Practice in Science Education* (EPSE) project lends support to the view that assessment instruments can be significant levers of change in practice (Millar & Hames, 2006). Teachers were provided with banks of assessment items on a science topic, which implicitly defined learning objectives more precisely, and invited to use these in whatever ways they wished. They were later interviewed about what they had done with these materials and what they thought of them. It became clear that the provision of carefully designed assessment tools had led to considerable reflection on practice, changes in the timing and sequencing of instruction, and changes in the balance between teacher-led and more discursive lesson activities.

I began this section with the question: How might we justify the claim that a particular example of research-based guidance on 'how to teach X' leads to an improvement in practice? Another kind of response to this is to focus on the *process* of teaching and learning, rather than on the *outcome*.[6] Lijnse (2000), in contrasting developmental research with other research-informed teaching interventions, refers several times to 'didactical quality'. This term, however, is not defined, and no criteria are given that might be used to assess the 'didactical quality' of any piece of teaching. Would two independent observers necessarily agree on the 'didactical quality' of the same piece of teaching? Without explicit criteria, there is a significant risk that this becomes a kind of 'connoisseurship' judgment – in the last analysis, simply 'what the observer thinks is good teaching'.

Do we need the idea of 'didactical quality' anyhow, or is a measure of learning outcome sufficient (and better)? Could you have teaching of high didactical quality from which students learned very little? Or conversely, teaching of low didactical quality from which students learned a lot? I think it *is* possible to separate the ideas of good teaching and good learning, at least to some extent. Committed and interested students can learn from poor teaching, by going off and doing much of the work for themselves using books and other resources. I also think that we can imagine a genuine improvement in teaching leading to no discernable improvement in learning. I am reminded of a conversation several years ago with an American college lecturer who was spending a sabbatical term with us. He was very knowledgeable about the research-based teaching materials being produced for teaching physics at US college level, and about new texts that were explicitly informed by re-

[6] One reason for this may be that we lack confidence in the quality (in particular the validity) of the commonly used outcome measures, and know that many of these can be subverted – leading to false positives.

search-evidence of students' learning difficulties. He said that he had previously based his teaching of current electricity on Chabay and Sherwood (2002), and had used their book also for his teaching of Newtonian mechanics – but was planning to switch to using Moore (2003) for the mechanics. I asked him: "Do you think you will see an improvement in your students' results in the end of topic test?" He thought for a moment and said: "No, but I will feel more satisfied with how I am teaching it." A teaching sequence that is seen by the teacher (and by others) as more logical and coherent is surely an improvement in 'didactical quality' even if it does not lead to measurably better student learning outcomes.

So I think we can, and do, have a notion of 'didactical quality' (or 'good teaching') that is separate from the notion of 'good learning'. But I also think it is possible, and desirable, to try to spell out the characteristics of good teaching. They would involve the quality of the rationale for teaching the topic in a particular way, of the analysis of content, the sequencing of ideas and the links between them, the choice of examples, the choice of models and analogies and the way these were used, and so on. In other words, a mixture of domain-general and domain-specific aspects.

Even with such clarification, however, I think that widespread adoption of research-informed guidance on how to teach X is unlikely to result from the claim that it has higher 'didactical quality' – but is rather more likely if we can demonstrate improvements in learning outcomes. If we want to influence practice more generally, perhaps even at national level, we need to give higher priority to the development of instruments and methods to identify those students who have successfully learned whatever it was that we wanted them to learn, in order to provide the kind of evidence that stimulates change.

3 What should research-based guidance on how to teach X look like, and how should we regard it?

Let me now turn to the third question at the end of the introduction: what form should research-based guidance on 'how to teach X' take, if our aim is that this be adopted by many teachers, not just a few who are associated with the developers? In particular, how detailed and specific should it be? Many developers of research-based guidance have opted to present very detailed recommendations on lesson sequences and activities (for example, Adey *et al*., 1996; Berkheimer *et al*., 1988; CLISP, 1987; McDermott *et al*., 1996).[7] The products of the Utrecht developmental research programme are also of this kind (Klaassen, 1995; Kortland, 2001; Vollebregt, 1998).

There are good reasons for providing detail. Most fundamentally, curriculum developers may recognise that they have to produce a detailed teaching sequence, including the activities that students should engage in and the teaching materials

[7] There are many others. I have chosen examples where the full teaching materials are published and hence accessible.

that these require, in order to demonstrate – first to themselves, and then to others – that the design criteria and principles they had in mind can be used to make a workable teaching intervention. Developing a detailed programme is a way of testing a hypothesis. If successful, it establishes a basic level of 'proof of principle'. In the case of the Utrecht developmental research programme, for example, the primary aim is to develop a way of teaching science topics in which "students … at any time during the process of teaching and learning see *the point* of what they are doing" (Lijnse & Klaassen, 2004: p.539, emphasis in original). It is not evident at the outset that this can be done for any given science topic. The products are intended to show how it might be done (and hence that it can be done). Curriculum developers may also feel that detailed guidance is necessary to communicate their ideas and intentions clearly to others, in particular potential users. This is particularly important if some aspects of the teaching are novel or innovative.

Against this, however, we must set the fact that good teaching is not simply a matter of implementing someone else's lessons, by following detailed guidelines provided. As already discussed, a teacher's decisions and actions must draw on locally specific knowledge that cannot be included in general guidance, however detailed. For this reason and others, any published teaching intervention is always modified when implemented. In part, this is also a matter of 'ownership' (Ogborn, 2002); few of us find that we want to use someone else's teaching approach and materials without modification. Modifications may also arise from imperfect understanding of the developers' intentions, or a wish to align their suggestions with existing practices and preferences, or with personal values.[8] Some of these modifications are unimportant – changes in features that are not central to the developers' intentions and which could, anyhow, have been different. But some modifications may undermine the principles on which the intervention is based. For curriculum developers, a key question therefore is: how can a teaching intervention be specified and communicated to potential users, so that the changes that are inevitably made when it is implemented do not damage its 'essence'?

One way to do this might be to say explicitly which details or aspects of the approach are believed to be critical to its success. Viennot (2003) discusses the importance of 'critical details' in the teaching of several science topics. Andersson and Bach (2004) take a similar approach, by identifying six specific conditions that they believe, in the light of the research literature, should apply to any effective teaching intervention in simple geometrical optics (Figure 1). Their guide for teachers (Andersson & Bach, 2003) then contains an analysis of content, an overview of known student learning difficulties and common misconceptions, suggestions for some lessons and activities, and diagnostic questions and tasks that teachers might use to find out which students have and have not achieved specific learning objectives.

[8] Lijnse (2003) (reprinted as chapter 9 in this volume) acknowledges that such modifications are inevitable when he writes: "In each … [class], the teaching-learning process will without doubt meander in a somewhat different way around the main path" (p.23) suggested by the guidance provided.

- From the beginning, a need for the key idea of optics is created, namely that light exists and propagates along straight lines between sources and effects.
- From the beginning, the students are offered opportunities to use the key idea of optics as a tool to explain real-world phenomena, such as the size and shape of shadows and illuminated areas.
- The teaching clarifies that light propagating between sources and effects cannot be seen.
- Only after having established the key idea of optics is seeing explained by light entering the eye from the object seen.
- Only after having established the key idea of optics and explained seeing are techniques for showing the path of light introduced, such as blowing smoke or letting light from a slit interact with a sheet of paper. If these techniques are already introduced during the very first lessons, the students may easily get the impression that one can see light propagating in space, i.e. that seeing is a separate ability that does not depend on light entering the eye but rather on the eye looking, sending out glances, etc.
- Teaching about image formation takes as its point of departure the idea that when light that diverges from a point P on an object and due to refraction or reflection meets again in another point P_1, and image of P appears in P_1, and the corresponding idea for virtual images. Only after these ideas have been carefully discussed are conventional geometrical techniques for constructing images introduced.

Figure 1 – Conditions for improved learning of geometrical optics (from Andersson & Bach, 2004).

This way of specifying conditions that a research-informed teaching intervention should satisfy, regardless of the merits of the six conditions that Andersson and Bach propose, has some attractions. It enables the central features of a research-informed teaching intervention to be set out briefly and clearly, making them relatively easy to assimilate. It is relatively easy to identify implementations that comply and do not comply. And the claim that teaching interventions that satisfy these conditions lead to better learning than ones that do not is testable, if we can agree on an outcome measure. Viennot and Kaminski (2006), for example, provide evidence of the impact on learning outcomes of a 'critical detail' in the teaching of optics.

If, for whatever reason, we believe that very detailed guidance on a teaching intervention is necessary, it is essential that this be accompanied by a commentary explaining the rationale for the many choices and decisions involved in the design of the intervention, distinguishing those considered important (perhaps even critical) from those that are not. This cannot be left to be inferred from the teaching materials themselves. Only by providing this kind of meta-knowledge can the developers hope to 'control' the nature and extent of variation in implementation. The challenge is to find a way of doing this that leads to it being read and acted upon. Experience suggests that teachers using a new teaching intervention often infer what they are supposed to do in the classroom from the student materials alone, and read the associated guidance for teachers only as a last resort. This can result in modifications that deviate considerably from the designers' intentions. This becomes increasingly likely as the teaching intervention is disseminated further from the immediate environs of the development group.

Having been involved in several major curriculum development projects that produced detailed teaching materials (Campbell *et al.*, 1994; Millar, 2006), and observed how these were used, I am increasingly drawn towards less detailed ways of communicating the essence of an intervention – supported if necessary by exemplary teaching materials to communicate ideas and possibilities clearly. I suspect we would do better, if our aim is to influence the practices of many teachers, to envisage guidance on 'how to teach X' as a template, or framework, that allows but also constrains variation, rather than as a blueprint that tries to specify everything in detail. I do not think we know nearly enough about what such a template might look like if it is to be effective. Again this is an issue which merits much more attention than it has so far received.

Finally, I want to say a little about how we should regard research-based guidance on how to teach X. In the approach taken by Andersson and Bach (2004), the contents of Figure 1 could be seen as a 'domain-specific theory'. This could be used to construct many different teaching interventions – each a separate artefact based (in part) on that 'theory'. Writing of the Utrecht developmental research programme, Boersma *et al*. (2005) put the relationship between theory and artefact the other way round. For them:

> "The aim of developmental research is not the development of curriculum materials, but the development of a domain-specific didactical theory. Curriculum materials developed in developmental research are used as research instruments, necessary to develop a didactical theory." (p.87)

Lijnse (1995) suggests that the teaching and learning materials, presented in a certain way, *are* the theory:

> "A detailed description of possible didactical structures for a certain topic may be given in … 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 … The scenario can be regarded as a rather detailed domain-specific theory for the teaching of a specific topic." (p.196)

These are rather problematic claims. If the 'theory' cannot be articulated separately from the artefact, then we cannot say anything about the principles on which the artefact was designed. These are entirely tacit – embodied in the artefact itself and not separately expressible. It is hard to believe that this reflects accurately the process of development. It seems more likely that the design of a scenario is based on a range of considerations that could be articulated, some of which are content-independent whilst others (such as detailed content analysis) are domain-specific.

If a detailed research-informed teaching intervention is produced, I think it is more straightforward to see it, not as a domain-specific theory of the teaching of X, but as an artefact that is based on knowledge, some of which comes from research. Some elements of this knowledge might be termed 'theory'. This artefact is essentially a hypothesis – about how the underlying principles might be 'translated' into an effective sequence of actions and about the outcomes that might ensue. Civil engineers – to draw on the 'engineering' analogy – do not see every new bridge that they build as a new local 'theory of bridge construction', but as a new (and possibly novel) artefact based upon accepted theoretical knowledge, applied to a specific local situation, to achieve pre-specified outcomes (in particular to carry the load it has to carry without falling down).

Treating the product of developmental research as a domain-specific theory blurs the distinction between the artefact and the design principles (or theory) on which it is based – and makes these design principles less visible and less easily testable. We ought, I think, to embrace the 'engineering' view of research-informed curriculum development more whole-heartedly – and resist the temptation to be drawn back into seeing ourselves as social scientists whose primary interest is in theorising. The task of making better artefacts, and showing that they really are better, is quite enough. The key to increasing the impact of research on practice is to demonstrate, in as clear a fashion as possible, that specific research-informed teaching interventions lead to significantly better learning outcomes, as measured by instruments that are widely seen as valid and reliable measures of outcomes that we value.

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4

Curriculum development as practical activity

Abstract

I discuss science curriculum development as a practical activity, and question how far we can go in giving it a firm basis in knowledge of how to do the job. At least any such knowledge would have to take account of the extent to which each development is local and specific, their relationship to issues and ideologies current at the time, the question of 'top-down' versus 'bottom-up' development, the role of didactic inventions and creativity, the relationship of development to research, and the question of ownership.

Introduction

We are here to honour Piet Lijnse at the time of his retirement, and I am pleased and proud to have been invited to contribute to this symposium. I feel that I must begin with a number of disclaimers, perhaps even confessions. Having, like Piet, spent a working life involved in curriculum change in science education, I at first welcomed this opportunity to reflect on the nature of that work. But I quickly came to realise that most of my thoughts amounted to purely personal justification: trying to find arguments that showed how right I had been all along! I do not think that in what follows I have managed to avoid this trap, but at least I am warning you about it in advance.

Thinking about the title of the symposium, I at once wondered why anyone would want a theory to inform the development of teaching and learning sequences. The answer, it seemed to me, must be that it would somehow make the process more scientific, more technical, and thus make it less prone to failure. For that, in the largest sense, is one main reason for trying to achieve scientific and technical knowledge, is it not? With it, what looked like an art, depending wholly on talent for success, could become something anyone sufficiently well versed could do successfully. Of course, although we want our bridge builders and doctors to be gifted, we even more want them to know as much as possible, and not to rely on talent alone. The value of science and technology in reducing the need for genius is indisputable, when one can have it. The question is, are we anywhere near the point where teaching materials can be designed by anyone who knows enough, without relying on their individual gifts? These were the kinds of question that were fermenting in my mind. You can see how easy it would be to answer "No", and in doing so to appear to lay claim to a special talent for myself. At the same time, I have, over the years, seen many examples of material developed for teaching, and what to my mind most distinguishes them is not their solid foundation in knowledge of how to teach, but the flair that they do or do not show, the "rightness" that a good work of art or a well-designed artefact possesses.

As a young man I was asked to lead – with Paul Black – a national curriculum development project in the UK. That was *Nuffield Advanced Physics* (Ogborn, 1971). I thought of it as a unique experience. Then, thirty years later, I was asked to do the same again, for the Institute of Physics project *Advancing Physics* (Ogborn & Whitehouse, 2000; Ogborn & Whitehouse, 2001). Rarely is anyone invited to make the same mistakes twice over. At the risk of over-personalising what I have to say, it is from this standpoint that I have tried to think about the nature of curriculum development in the sciences. I offer these remarks, not as a carefully worked-out theoretical scheme, nor as a well-researched narrative, but rather as a patchwork of thoughts that occur to me as I look back and reflect.

Before I get started, I should commend to you another account, by Myron Atkin and Paul Black, of their experiences in curriculum change, in their book *Inside Science Education Reform* (Atkin & Black, 2003).

1 Local specificity

The Devil, it is said, is in the details. This seems to be very true of curriculum development. The early large-scale developments in the USA, notably the Physical Sciences Study Committee (PSSC, 1960), Harvard Project Physics (Rutherford, 1970), Chem Study (Campbell, 1962) , the Chemical Bond Approach (CBA, 1962), and the Biological Sciences Curriculum Study (BSCS, 1959), all hoped to have an influence well beyond the confines of the USA. So they did, but more often through the fact of their existence than through direct adoption in other countries.

The first reason is simple: they were all finely tuned to the needs of the American educational system. PSSC made good sense for a system in which high school students began their first substantial study of physics at age 16. But in the UK, where physics was taught from age 11, it made little sense. As a result, the sponsors of PSSC complained about it not being "translated into English".

A second reason has to do with ownership and creativity. The main reaction of teachers and educators in European countries to these US projects was to want to try to do it for themselves. Local pride, and local awareness of essential subtleties, played an important role. As a result, over the 1960s and 1970s, a variety of projects burgeoned throughout Europe: for example PLON in the Netherlands (PLON, 1985) and "Ask Nature" in Denmark (Thomsen, 1978), besides the dozen or more projects sponsored by the Nuffield Foundation in the UK.

Each was very specific to its time and place. New teaching programmes have to be a very good fit to local circumstances, taking account of different structures of schooling, of different times available for teaching, of the varying prior knowledge of students, of the expectations and preparation of teachers, of official rules and regulations.

But could we not all agree about the essential structure of physics, chemistry or biology, and about good ways to approach the central concepts, and then tune these in detail to local circumstances? It turns out not to be so. Just as good architectural solutions often arise from turning the disadvantages of an awkward site to positive advantage, so good educational solutions often capitalise on local problems and constraints, turning what looks like a difficulty into an opportunity.

An example might be the emphasis in the UK projects on first hand laboratory work for students. UK science teachers found their school laboratories full of old pre-war apparatus. Students disliked the excessive amount of theory, with concepts not much linked to experimentation. The solution was to develop new equipment and to promote the notion of exploratory play with apparatus. This kept pupils and teachers happy, and was in tune with the general empiricism of Anglo-Saxon culture. The developers were surprised to find that teachers in France, Italy, Spain or Portugal were unimpressed, giving rigorous theory a much higher valuation than did the empiricist English.

Perhaps the general message is that we are all rather blind to the specificities of our local circumstances. They are "just how things are", and we are surprised when we find that they are very different for others. Any theory informing the development of teaching materials thus needs to be highly local and specific, finely tuned to local specificities.

2 Issues, ideologies and slogans

Development projects naturally address current educational issues. In the UK, the main educational issue actually changed while the first Nuffield projects were being developed. It changed from being how to develop a lively up-to-date science for selective secondary schools, to being how to develop a convincing science programme for the all-ability comprehensive schools just then being introduced.

The UK had, up until the 1970s, a divided system of secondary education. About 25% of the school population was selected for the academic "grammar" schools. The rest went mainly to "secondary modern" schools, whose curriculum was at best loosely specified. The Nuffield Foundation's projects initially focused on the science curriculum for the selective schools. This was certainly in need of repair – dull and routine, with its structure largely inherited from the great 19th century textbooks. The new slogan was "Science for All". But, like most slogans, it did not mean what it said. It meant, science to appeal to all the 25% selected for grammar schools, not just to future specialist scientists. It did not remotely mean science for students of all abilities.

However, during this period the movement to replace the divided system by a comprehensive schooling system, actually "for all", gathered strength. Thus in the UK, the issue became how to develop science courses genuinely designed for the whole school population. This became something of a national obsession, not shared by other countries. One slogan devised for this was "Relevance".

Complex issues need complex solutions, but they generally get simple slogans to encapsulate and make memorable these solutions: "Relevance", "Ask Nature", "Science for All", "Hands On", "Science Workshop", "Learning by Doing". Mao

Zedong had a genius for inventing them, in a very different context.

Be wary of these slogans. They are needed, even essential, to help people remember the point and perhaps to focus energy and enthusiasm. But they rarely speak plainly. I remember being asked near the start of my second development project *Advancing Physics*, what its slogan would be. I was at first embarrassed to find that I had no good answer. Maybe “Variety”, I said – if you want to appeal to more people you have to offer more ways of being attractive. The answer suggests its own limits. It cannot be right to focus a whole course on being attractive, at any cost. So there must be a basic truthfulness to the nature of the subject – in this case physics. But now this is not a slogan, but the statement of a complex problem. I cannot say that I am sorry, even if it makes it hard to tell people what is the ‘essential new idea’ behind *Advancing Physics*. In fact, I am suspicious of any educational development that passionately believes in its own slogans. I do not much believe in one-shot solutions – ‘magic bullets’.

I conclude that a theory that provides guidance on producing teaching materials will suffer the same difficulty: that simple slogans encapsulating its ideas are needed, but are also dangerous.

3 ‘Top-down’ versus ‘bottom-up’

I vividly recall my introduction to the question of whether curriculum change should proceed from the top down – from experts to teachers – or should be bottom up, collecting ideas and good practice from teachers themselves. I was sitting in a grass-roofed hut in the Kruger National Park in South Africa, alongside Professor Dieudonné, one of the famous Bourbaki mathematicians. We were in South Africa to talk about changes in the science and mathematics curriculum: I to talk about *Nuffield Advanced Physics* and Dieudonné to talk about the changes in the mathematics curriculum in France.

He learned that I was a secondary school teacher. Graciously but sceptically, he asked me where the key ideas for *Nuffield Advanced Physics* came from. Who guided our work from above? Proudly I answered, “From us – from the team, all of us teachers.” “No”, he replied, “You misunderstand. Who really supplies the main ideas, the fundamental basis of the course?” I gave the same answer. “Impossible”, he said, “New ideas come from the University – *par definition*.”

Yet in fact, from his point of view, he was right. In mathematics, the desire for change stemmed from deep changes in mathematics itself. The Bourbaki and others had sought to place mathematics on an entirely new rigorous foundation. So mathematicians found school mathematics almost unrecognisable *as mathematics*. They wanted a fresh start, beginning for example with the logic of sets. France was not alone in this movement for ‘the new mathematics’. The idea was sweeping the world.

It has to be said that the introduction of ‘modern mathematics’ was not a complete success. Parents were disturbed to find their young children coming home from primary school talking of things the parents had never heard of: sets, unions, disjunctions. Many older teachers felt that alien ideas were being imposed on them; that their hard-won teaching skills were suddenly valueless. Nevertheless, the changes that had taken place in mathematics were real and were valuable. Gradually, as new teachers replace older ones, some at least of the new thinking has become naturalised in schools.

A recent change in the sciences is the growing importance of digital imaging, together with new ways of imaging structures down to the molecular scale. Besides its many applications, digital imaging and communication is a whole new subject matter for which teaching methods need to be created. We attempted some of this in *Advancing Physics*, to the point of starting the physics course with an ultrasound image of a baby in the womb.

Sooner or later, changes in scientific subjects start to affect the school science curriculum. In the case of biology, it has been sooner rather than later: DNA is, at fifty years of age, already firmly part of school biology. In physics, change is patchy, often later rather than sooner. Some glamorous parts of astronomy are present, if only as an option. So are simplified accounts of the quark structure of nucleons and mesons. But, with rare exceptions, the revolution introduced by quantum field theory remains unremarked. So indeed in large measure do Maxwell's equations, and relativity, ancient though both are.

Thus some curriculum change in science and mathematics is necessarily 'top-down'. To return briefly to the hut in the Kruger National Park, it was disingenuous of me to tell Professor Dieudonné that *Nuffield Advanced Physics* simply worked 'bottom-up', from teachers' own ideas. Certainly we avidly collected ideas from the best teachers we could find. Fundamentally, though, this project was also 'top-down', in the sense that the course was designed and built by a small central team, and then disseminated through a process of trials, and supported by a large scale training programme over several years.

Not all necessary changes in the curriculum derive from changes in the subject matter. Often, the problems lie elsewhere, in changes in the nature of schooling and of society.

In some such cases, the natural way to work is 'bottom-up', from teachers' own expertise and ideas. An example, again from the UK, is the *Secondary Science Review* (West, 1983). Directed by Dick West, this did *not* attempt to create central teaching materials to solve its problem. Its problem was whether there could exist a viable science course that might meet the needs of all secondary pupils. The Review set about collecting and describing examples of good practice, and making them more widely known. It was driven by its own ideology, that of valuing the expertise of the practitioner. And indeed it did succeed in building many groups of increasingly self-confident teachers who were made to feel that their efforts were valued and valuable.

I cannot say that a large body of high quality teaching material emerged in this way. Indeed, the project published some rather unremarkable stuff. But that was not really the issue. The issue was political: to persuade parents, head teachers, other teachers, and local and central government officials that solutions could be found and that teachers could be trusted to find them. In this, the Review succeeded.

I am sure that there are, and will be, other examples where 'bottom-up' is best. An instance may be the use of computers in science teaching, particularly computer-based laboratory work. This does involve changes of a fundamental kind, but changes essentially of classroom practice. Having teachers invent ways of exploiting these devices, and making their ideas widely known, may well be the best way forward.

Let us not forget, also, the large amount of 'invisible' curriculum development that goes on through the pages of teachers' journals, and at meetings for teachers, where good ideas are presented and exchanged. Indeed, I would think that any country should give high priority to stimulating such an infrastructure, to support and develop a sense of professional community amongst science teachers. The Internet offers scope for doing more in this direction.

It is surely bottom-up development that is most in need of a good account of how best to develop new teaching ideas, if it is to avoid purely ad hoc reliance on the ideas the practitioners involved happen to have. But in my experience, however, teachers are highly resistant to 'theory', scorning it in favour of their own practical know-how. This is I think a real obstacle in the path of any vision of theory finding wide use in practice.

Involving teachers directly in curriculum development is widely seen as the right way forward. Myron Atkin and Paul Black (1996) report how, in the majority of the international sample of development projects that they surveyed for the OECD, considerable responsibility was devolved to teachers for deciding content and approaches.

At the same time, I think that there remains a role for strong leadership and vision. Teachers will identify with a new course not only because it came from other teachers, but also because it offers something strong and inspiring with which to identify. It really helps to think that you are part of something important.

4 Inventions

Every way to teach a given idea or skill was once invented by someone, and passed on to others. In science their traces are often to be seen in the science teaching apparatus stored in the laboratory cupboards.

Often new technologies suggest new ways to teach. In chemistry, one such was the introduction of glassware for small-scale preparation of compounds. In biology, schools had to equip themselves for doing microbiology. The digital revolution swept away most of the analogue electrical meters in schools. And now, computer based instrumentation has the power to change the way we teach much of experimental science. I am not sure how the mobile telephone and digital camera will change the way we teach about electromagnetic waves and digital communication, but I am sure they will.

My own personal interest, however, has been more in the invention of new ways to construct and present theoretical arguments. There are many important parts of science that languish untaught in schools because the theory is simply too difficult.

One example is thermodynamics. The purely macroscopic theory is highly abstract and inaccessible. The statistical microscopic theory is more easily interpreted, but seems to require difficult statistical arguments. Thirty years ago, in *Nuffield Advanced Physics*, we found a way through these difficulties, using random simulations.

I may as well tell you the origin of this line of thinking, to illustrate the chancy nature of didactic invention. In an early conversation about *Nuffield Advanced Physics*, Paul Black and I agreed that thermodynamics was probably too difficult for us. So I 'wasted time' dreaming of possible answers. Books like Henry Bent's *The Second Law* showed that thermodynamics need not be dull and unintelligible. A chemistry professor told me of his way of introducing the Boltzmann distribution, which struck me as incorrect. He agreed, but said that he did not know how to do better. Then, one sunny afternoon in Worcester, I had the idea of moving plastic chips representing quanta of energy around on a grid whose sites represented oscillators in a crystal. Astonishingly, the Boltzmann distribution seemed to appear. Paul Black recruited a mathematician to prove that the idea was right, and everything fell into place. Today, these ideas are alive and well in chemistry courses in the UK.

A second long-standing obsession of mine has been inventing ways of exploiting the computational approach to solving differential equations to simplify the teaching of mechanics and other topics. This obsession also started in a very unlikely way. About January 1966, I was worrying about how to teach the wave mechanical account of the hydrogen atom. It occurred to me that one could solve the time-independent radial Schrödinger equation very simply, step by step. This could be done graphically, without any heavy arithmetic or algebra. I was overjoyed to see the form of the radial wave-function for the ground state emerging on my graph paper.

Then I started worrying about how to reach that point with a class of students. I saw that the same graphical methods could be used for the first order equation for exponential decay, and for the second order equations for uniformly accelerated motion and harmonic oscillations. This was obvious to me because I had been lucky enough to be taught at Cambridge by the great Douglas Hartree, whose lectures inspired us with the notion that very simple step-by-step arithmetic methods could both solve difficult problems and illuminate their inner structure.

The result was that *Nuffield Advanced Physics* used computational methods to understand simple differential equations, at a time when the only way for a school to use a computer was to send a deck of Hollerith cards to the computer centre of a university or a commercial company.

The more general question now is whether computational modelling can radically simplify and illuminate the reasoning needed in mechanics and other problems. It seems clear to me that it can. I have no insight at all into why this didactic invention has proved so difficult for most teachers to accept.

Anyway, for me this process of *la transposition didactique* is as fascinating and intellectually demanding a process as anything I know. But it is also wayward and subject to chance, as is anything creative.

5 Research

Perhaps you are expecting me to tell you how crucial research in science education has been for curriculum development, and how important it is that research underpins future development. Could there be a hint of your own self-interest here?

The fact is that research has been important, but only in a limited number of cases. In France, the curriculum in optics was reformed on the basis of very good research by Laurence Viennot and her colleagues into problems of understanding light. Paul Black and Wynne Harlen devised a primary science programme based on their research project SPACE (Black & Harlen, 1990). In the USA Lillian MacDermott, Joe Redish and Barbara White are amongst those who have built teaching materials around research results (see, for example, Redish, 2003).

Research can also be valuable in buttressing support for an idea about how or what to teach that, without evidence of its success, would be easy to reject. An excellent example is Laurence Viennot's work on re-introducing important elements of rigour in teaching science (Viennot, 2009). Just because the idea is currently unfashionable (to put it mildly), good evidence that students actually appreciate it is crucial.

Important though these efforts are, I remain a shade sceptical. Research can often point the way to the existence of a problem. It less often points directly to the solution. An example is that we can now be quite sure, from a massive body of research, that students find Newton's laws unbelievable, and create for themselves ideas about forces needed to keep objects in uniform motion. I have my ideas about where the deep difficulty lies; so no doubt do you. But none of us seem to be able to break through.

This means being modest about what research can contribute to curriculum development, and admitting that there are cases where insight, intuition, experience of teaching and deep knowledge of the subject are at least equally valuable sources of ideas about how to teach.

6 Ownership

Stimulated by the experience of first leading the *Advancing Physics* team and then of standing back, letting go and watching the teachers of the course take over, I wondered who can best be said to own a curriculum development (Ogborn, 2002). One of the strongest conclusions to come out of decades of studies of innovations is that they succeed best when teachers feel a sense of ownership of them. It seems to me that the owners of a course are the teachers who teach and transform it, not those who originally develop it.

This is a bit hard to accept if you, as the developer, have put body and soul into designing a piece of teaching to be as good as you can make it. But it is inevitable, because teachers necessarily transform any ideas when they interpret them for themselves and turn them into something that they actually do in the classroom. Understanding is invariably a transformative act, with new ideas refracted though one's own thinking so that new and old fit together as well as possible. Just as any author is always surprised at the enormously varied constructions readers put on what they wrote, so whenever you go to see a teacher using your ideas, you must expect to be struck by how the ideas have been changed.

For this reason, there simply is no such thing as ‘doing exactly what the developer intended’. There was a time, after the first wave of curriculum development, when developers saw (often with horror) what was happening to their materials, and entertained vain hopes of creating ‘teacher-proof’ materials. More positively, what one can often see is a teacher inspired in some important way by the materials, and making something fresh and personal out of them. This is why, for *Advancing Physics* we decided that it was important to design the course explicitly to give teachers a lot of freedom and choice, for example by supplying alternatives for essentially every activity. Although this caused a lot of initial anxiety, as teachers worried about how to choose between the many alternatives, most have now come to value the opportunities it gives them to make the course their own. The course’s active teacher email network is full every day with messages from teachers exchanging ideas and yet more alternative resources, as well as asking each other how they approach a given topic.

From this point of view there is a further perhaps uncomfortable conclusion to be drawn, about whether a really well-designed and soundly based piece of teaching ought to be taken up and generally adopted by teachers. The seemingly simple question, “If this is the best, why should everybody not do it?” has to be given a subtle answer, namely that ‘the best’ is an elusive thing, not always the same for everybody. A teacher willingly and enthusiastically teaching an ‘inferior’ course, will I think usually do a better job than if obliged to teach a ‘better’ one. At the least, a theory providing a basis for designing a teaching sequence needs to take into account the crucial need to recruit teachers’ enthusiasm for the material, and to accept that when this is not achieved, teachers may be better doing something else to which they do feel the necessary commitment.

7 Cometh the moment

The possibility of curriculum development depends on being lucky in catching the right moment. There are times when teachers are ready for change. There are times when the political will is there. There are times when the resources can be found.

I was very lucky to be around at two times when curriculum development was possible, even welcomed. The first occasion was one when the example of what could be done shown by the USA combined with a new post-war sense of the desirability of change, encouraged the Nuffield Foundation to put substantial resources into science education. The second occasion arose because there was to be a generally welcomed and overdue broadening of the curriculum. This combined with the fact that the professional association of physicists, the Institute of Physics, was worried about the decline in numbers of students taking physics, and had (briefly) some money to spare. So *Advancing Physics* happened.

Thus my final message to those who would like to be involved in curriculum development is: 'be lucky'. Do your best to live in interesting times.

Postscript

I would like here to acknowledge the influence on my thinking of the political philosopher Michael Oakeshott, despite his deep scepticism about the possibility or desirability of rationally planned change or reform. I commend to you his book of essays *Rationalism in Politics*. Oakeshott writes eloquently against what he calls "the invasion of every department of intellectual activity by the doctrine of the sovereignty of technique". Recent manifestations of it include the rise of managerial approaches to solving social problems, for example the setting and monitoring of 'targets'.

So, if there were to be a theory of the kind envisaged in this symposium, I would warn against it becoming too dominant. Tradition, experience, and the surprises that talented individuals can achieve, have their role to play too.

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5

Lessons I have learned

Abstract

As almost all that is important has already been dealt with in the previous presentations, I will present a more personal view by reflecting on my thirty-six years of work in physics education. For example, what might we have learned from the Dutch PLON project in the 1970s and 80s, that is still relevant today? Do we now know more about how to teach successfully in context? Because since then, much research has been done on pupils' conceptions and on strategies to improve conceptual learning processes.

Our own work has tried to contribute to this effort by trying to find research-based 'didactical structures' that could potentially improve the teaching and learning of X's. Has this research now resulted in didactical 'theories' that are useful for curriculum developers and teachers? If not, why not?

Introduction

This contribution, which you might call my 'scientific' swan song, will mainly be a personal reflection on thirty-six years of work in 'didactics of physics'. What have been the dominant events and people that shaped my work and thinking? So, it will not so much be a 'traditional' depersonalised scientific paper, but more a kind of narrative which may illustrate that I am still in touch with the newest fashions of our educational trade.

For me it all started in 1973 when, to my own surprise, I joined the Physics Education Group of the University of Utrecht. Actually that was a kind of last resort, because at the time I could not find a decent research position in physics, even though I had just finished a quite successful PhD. During my PhD work, several aspects of being involved in research had often given me a great feeling. Digging deep into and then finding a solution for a problem was exciting. Particularly because I felt it to be embedded in and part of a much larger international effort. Together we made progress, both theoretically and experimentally. So that an international diversity of experiments finally resulted in a common theoretical explanation. Once I even enjoyed the Eureka feeling of having found an important step, a small 'piece of knowledge' about nature, which nobody else in the world yet knew. And from all this I got the, admittedly rather naive, idea that research *quality (*and not quantity) is the one and only all-decisive factor for a successful scientific career.

It was because of this experience that from the start of my work in physics didactics I have been trying to find a way to set up research in *that* field as well – even though that was not at all a self-evident thing to do, because at the time research in didactics hardly existed in the Netherlands.

Unfortunately, since then, my research in physics has not only served as a lasting reference but also as a lasting hindrance. For instance, as I had to learn to accept that while solutions in physics mostly *do* work in reality, solutions in physics didactics work mostly only in the minds of their inventors. I often asked myself to what extent it can be said that research in science education is really a *scientific* activity. Of course you might rightly say that this only reflects the almost proverbial arrogance of a physicist. But after all, isn't it the case that in physics they are searching for a theory of everything, while we just heard today that in didactics we do not even succeed in having a valid theory of anything.

1 Curriculum development

The first project I worked on was a curriculum experiment to introduce some quantum physics at school. Because of it, I attended in 1975 my first Danube seminar in Hungary to report on our experiment. It was then and there that I met both the legendary George Marx and the now equally legendary Jon Ogborn for the first time. Both have had their own important influence on me. George opened my eyes for the fact that you need to be a really excellent physicist, with a broad and deep overview of the discipline, if you want to translate new fields of physics, such as quantum ideas, to lower teaching levels in a successful innovative way.[1] While Jon has always served as an unreachable (for me) standard of excellence in curriculum development and research, starting from the didactically brilliant *Nuffield Advanced Physics* curriculum up to the equally innovative *Advancing Physics* curriculum. Recognising my own limitations, both as a physicist and as a curriculum developer, I could not do better in my quantum mechanics project than steal a lot of their ideas. Finally this ended up in a book for the general public, in which I used the stolen ideas to answer the explicit questions that I myself had wrestled with in coming to some understanding of the topic.[2] A younger colleague recently told me that from reading my quantum mechanics book, finally he had not only understood, but also come to appreciate the idea of a problem-posing approach (see further on). This was much to my surprise because, if he is right, it must have been a problem-posing treatment *avant la lettre*.

It is typical of curriculum development, I think, that not only the first but also the last curriculum project I was involved in, though this time only as an advisor,

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[1] Apart from George's writings on, e.g., atoms, entropy and chaos in the school, a more widely known proof of my statement is Feynman's Lectures on Physics and his small book on QED.

[2] Thanks to the blessings of the internet, you may read the following at http://blogs.discovermagazine.com/cosmicvariance/2006/09/28/quantum-mechanics-made-easy: "The best introduction to Quantum Mechanics for laypersons I have ever read unfortunately exists only in Dutch: Lijnse, PL: Kwantummechanica, Het Spectrum – Antwerpen, 1981. This book contains the best description of the (in)famous 2 slit experiment I've ever seen, and moreover, the author doesn't shy away from simple mathematics, such as (single variable) calculus. The book is actually aimed at final year secondary school / high school students."

concerned the introduction of quantum physics at school. So it would be tempting to compare the products of both projects. And then answer the question: in what respect has many years of international experience in curriculum development and research indeed resulted in some positive difference regarding their didactical quality?[3] If any, of course. And it would also give some useful insight into the irrational factors that determine curriculum innovations if we knew better why the first successful experiment never got beyond its experimental stage, while the intention was to implement the second even before its development had started. In the end, however, due to the recent curriculum reform in my country, the materials of the second project will also finally not be implemented. It appears that they will be replaced by yet another Quantum Physics module. Nobody will be surprised, I suspect, to hear that this final module seems to have been written without any recognisable influence of, or reference to, everything that has been proposed or tried out before. Apparently, that is how things are done in curriculum innovations.

The PLON project, which has become world famous except in the Netherlands, was the second and major project I participated in. Its fame was due to its focus on context-rich physics teaching. About PLON, Gunstone (2004) recently wrote: "It is chosen here to represent context-based physics curricula because it has been the leader in this focus."

In my opinion, curriculum development is in the first place a creative activity, but having said that, this creativity should rest on a solid background of didactical knowledge and experience. It asks not only for a thorough mastery of the subject matter, but also for a well-developed view on 'good teaching', and the didactical knowledge and creative skill to put that view into practice with sufficient quality. And, to ensure that quality, apart from being aware of similar curriculum experiences abroad, one should also know about all kinds of practical implications said to result from educational and didactical research. So, actually, it is a rather difficult activity. And thus wouldn't it be a great help if we would have more empirically tested didactical theory that could guide such development?

At that time, however, such theories were not available. Nevertheless, we did a rather good intuitive job, I think, in developing a new context-rich approach to physics education. Good enough anyhow, to attract some people from abroad who wanted to study the project in more detail.[4]

In retrospect, PLON was in many respects maybe too far ahead of its time as regards its use of contexts, its focus on active learning and participation of pupils, its attention to reflection and meta-cognition, cooperative learning and communication skills, differences in learning and teaching styles, and so on. And therefore it is

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[3] The concept 'didactical quality' appeared not to be self-evident at the symposium. In Lijnse & Klaassen (2004) (reprinted as chapter 10 in this volume) we have given some criteria to operationalise the term.

[4] Among whom an Irishman from York named Robin Millar, who since then has always remained a supportive critic of the work in Utrecht. His main influence on me consisted of his urgent advice, during the first PhD Summer School, to be more explicit in expressing my professional opinions. Finally, as this chapter may show, it worked, though not necessarily for the better!

a bit ironic, I think, that the present broad emphasis in the Netherlands on the so-called concept-context approach seems to make hardly any use of the PLON experience, thus facing the same problems all over again. In particular as regards the relation between curriculum rhetoric and curriculum practice. These problems have to do with the fact that in a context-concept approach the main focus is still on the basic concepts, for which suitable contexts now have to be found. According to *my* interpretation of the PLON experience, we may now say that such an approach is based on some didactical misconceptions that lead in practice to all kinds of frictions, such as:

- The use of contexts is not always motivating, and certainly not for all pupils.
- Conceptual learning is not necessarily easier in contexts, on the contrary.
- The choice of suitable contexts is difficult and often hard to justify, while an appropriate didactical elaboration is not at all easy.
- It is very difficult to make a really functional use of contexts – that is to let them be more than just a new shell around traditional concepts.
- The difficulty of developing contextual teaching modules of sufficient didactical quality is severely underestimated, as it asks for expertise that first has to be learned.

Similar remarks can be made about the teaching, testing, and implementation of contextual modules. And these remarks are just as valid if we replace the word ‘context’ by the term ‘authentic practice’ (Bulte *et al.*, 2006). Progress in curriculum development, if it is possible at all, is apparently hard to achieve. I have to admit, however, that the PLON project did not sufficiently reflect on and report its pioneering experiences to really stimulate and support such progress.

As regards the didactical level, that is the interplay of teaching-learning activities, we were (or at least *I* was) convinced that we developed more understandable physics teaching. So for me it was rather disturbing when it became gradually clear that the cognitive learning effects of the experimental project were not clearly superior to those of ‘traditional’ physics teaching. It was still the case that only a small minority of the pupils reached a level of sufficient understanding, while the large majority were only able to survive the system – that is to be sufficiently trained to pass suitable tests.

In the 1950s, the mathematics teacher Van Hiele (1957) wrote an excellent PhD thesis on what he called “the problem of insight”, that is the problem of making pupils really understand what they are taught. In spite of the fact that, from our point of view, we developed quite innovative and updated teaching materials, apparently, we had not really succeeded in bringing this problem of insight much closer to a solution. Being mainly a group of idealistic former physics teachers, on the whole, our work remained didactically at the practice-based level of the experienced teacher. In that respect we had not made much progress.

A history that is repeating itself, I’m afraid, in the present curriculum reforms in our country, as a brief look on some of the many contextual modules that have been developed recently clearly shows. Does that simply mean that didactical progress is impossible or that, in spite of all the theoretical curriculum rhetoric, we still lack the necessary didactical micro-knowledge? Anyhow, I found the contrast between our idea of having developed better physics teaching and the disappointing effects of such teaching a rather sobering experience, which since then has determined my professional agenda. If curriculum development is not able to solve the problem of insight, as its primary aim is updating, could research in didactics be of any help in solving it, we might ask?

2 Research on teaching and learning

At the time, part of the answer to this question was already 'under construction'. At the 1976 GIREP Conference in Montpellier, some French researchers reported on their research.[5] But due to language problems and its, in our opinion, rather 'old-fashioned' context, I did not realise its importance. At least not until I got the thesis of a then still young lady, named Laurence Viennot, which dealt with the spontaneous reasoning of pupils about mechanics (Viennot, 1979). This more or less coincided with the 1979 GIREP Conference in Israel, where I happened to meet Rosalind Driver for the first time, just before she became a leading figure.

She gave a talk entitled "The pupil as scientist" which impressed me very much. In her talk, she described how she interpreted the *content* of pupils' utterances[6], in relation to a philosophical interpretation of the shortcomings of discovery learning and the need for a constructivist change. I was convinced that she made an important point, though I then hardly understood what it really meant.[7]

Both Laurence and Rosalind stood at the cradle of a new field of work that we now all know as research into pupils', and later also teachers', conceptions and on how to deal with them. I still remember my feelings of surprise and even disbelief when my chemistry colleague Wobbe de Vos reported that his pupils talked about yellow sulphur atoms (de Vos, 1985). Such problems with the introduction of particles are now well known, but when we wrote our innovative PLON units on the structure of matter we were not at all aware of them. This may also illustrate that even the simple idea of what later has been labelled 'trivial constructivism', i.e. that people *construct* new knowledge on the basis of what they already know, was not at all a common starting point in didactics. Meaning is constructed and cannot be transferred directly, which implies that the only thing I can now be sure of is that I am being misunderstood. (Which of course also applies to the former sentence.) Since then it has become clear, as I have written before, that taking trivial constructivism really seriously is didactically not trivial at all.

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[5] Although many of the basic ideas had already been published by the German Martin Wagenschein (1962).

[6] See also: Driver (1983). This was rather new, as in the 1970s the Piagetian approach (or what science educators made of it) of focusing on the logical structure of pupils' reasoning was quite popular.

[7] Unfortunately, as we all know, Rosalind couldn't be here any more. So, I was very glad that her students and successors, the Leeds boys Phil and John, of whom she always spoke very highly, agreed to be here to represent her memory. Although finally only John could really make it.

So, this research made plausible that the curriculum efforts of the past, including PLON, all suffered from the same shortcomings. In a certain sense, they all underestimated the problem of insight, i.e., of making all pupils take part in a gradual and coherent process of concept development, starting from where they are and leading to the intended understanding. And I am convinced that, again, this is also the case in the *present* curriculum effort in this country. It seems, however, that this is not considered to be a serious problem anymore, as the educational pendulum has swung away from attention to the less able pupils to attention to the so-called *talented* pupils.

Anyhow, I found this period rather exciting because now it seemed that indeed a research paradigm had been found that promised to enable didactical progress. This excitement was endorsed by the fact that internationally, and particularly in Europe, a growing number of people became involved in research in science education. So, it gradually seemed to become even a *respectable* field of research, which resulted in the setting up of PhD Summer Schools (Lijnse, 1994), and later in the foundation of ESERA (the European Science Education Research Association). To my surprise, I recently read that ESERA has now roughly a thousand members all over the world, of whom about sixty are in the Netherlands. I am still a bit proud that I have made a modest contribution to that development, though I am afraid that the summer school idea will forever remain my only professional initiative with some lasting impact.

Originally, in fact, this summer school idea was based on two pillars. The first was to provide a useful learning experience for PhD students, which has appeared to be rather successful. But the second was to provide a platform on which discussions could take place about productive research programmes of the participating research groups. However, this turned out not to be realistic, not least because such specific programmes appeared hardly to exist.

Nevertheless, as a result of the new overall paradigm, a large data base has been built of pupils' thinking about concepts and skills of school physics, and more generally about their common-sense characteristics, that people (researchers and teachers) should know about (although I do not think that they sufficiently do in the Netherlands). Subsequently, research-based improved ways of teaching were advocated that promised to have more success in reaching their intended aims. However, in my opinion, on the whole, this promise has not yet been fulfilled. Although, of course, there may still be some promising approaches that should be tried out further.

The momentum of the new paradigm has faded away and, as no new one has arisen, our research is again as scattered and undirected as it was before. Partly this failure has much to do, I think, with the fact that too much of the intellectual effort remained at a too general theoretical level. Dealing with topics such as constructivist teaching strategies and phases, whether we should aim at cognitive conflicts or not, whether we need weak or strong conceptual change, or should we after all still say conceptual growth. Together with discussions about types of discourse, the importance of the nature of science and the use of history and philosophy, and so on.

Interesting though such discussions may be, they leave too much of the proof of the didactical pudding to the teachers, meaning that the difficulty of applying them in practice spoils too much of their potentially fruitful differential effects. And thus we still have not learned enough from the past.

In our own work, as a follow-up to the PLON experience, I have always advocated much less ambitious goals, such as trying to find more effective ways to teach a certain topic X (Lijnse, 1995). In a discussion with Rosalind at the second summer school for PhD's, we agreed that it would be quite worthwhile to work on such a goal. And in fact, using some kind of design research, quite a lot of people have actually done so and worked in such a direction.

So we had, for example, a project on the introduction of particles in Leeds, a thesis on particles in the Netherlands, particles in Paris, particles in Berlin, and particles elsewhere (and everywhere). However, these efforts scarcely related to or built on each other. And as far as I know, nobody has as yet tried to synthesise these approaches, together with other research on models and modelling, discussing advantages and disadvantages, into some sort of applicable didactical 'theory' for the introduction of a particle model. This example is typical, I think. The more so as every researcher that takes him/herself seriously seems to develop his/her own theoretical approach (as we did, see below!). In general, in our field, research results are not critically synthesised into some kind of common empirically supported framework. Of course, we have quite a number of recent 'handbooks', as well as many other books on science education, but these are much more compilations of research, or 'research-informed' personal opinions, than productive critical syntheses of available empirical work. And thus as yet hardly any agreed-upon didactical knowledge has become available for teachers or curriculum developers. The new buzz word is 'evidence-based', but how much agreed-upon didactical evidence to build on do we really have? Apparently none, according to a recent publication in which the effects of some 'modern' teaching strategies are discussed (Kirschner *et al*., 2006). The idea of the didactical quality with which such teaching strategies are put into practice is not even mentioned, let alone be considered as a possibly relevant variable!

3 Our own approach

In designing 'trivial constructivist' teaching sequences, in Utrecht we have adopted what we call a problem-posing approach: the simple idea that pupils will probably be able to make more sense of the teaching process if, more or less, they know *why* they are learning *what* – a goal that can be reached if teacher and pupils *together* first pose the problems that gradually appear to ask for the concepts and skills to be taught. Or, in other words, if pupils are provided with an overall global motive and, by means of reflection at appropriate times during the teaching process, with content-related local motives.

In the recent report *Science education in Europe*, Osborne and Dillon (2008) wrote: "Traditional curricula in school science suffer from a number of difficulties.

Knowledge is usually presented in fragmented concepts where the overarching coherence is not even glimpsed let alone grasped – an experience which has been described as akin to being on a train with blacked-out windows – you know you are going somewhere but only the train driver knows where." Well, that is precisely the problem that our problem-posing approach tries to tackle. In a cyclical process of reflecting, designing and trying out, we aimed at designing teaching trajectories that, seen through the eyes of the pupils, could develop *for them* as meaningful and coherent story lines – story lines in which concepts and skills to be learned appear to be functional in view of the global and local motives set.

I have tried to depict the main critical steps in our story lines in schemes which I called their 'didactical structure', as the example on the next page may illustrate. This example describes the first introduction and elaboration of a particle model for 15-16 year old pre-university pupils. I have used this example before to illustrate how teaching *of* models and *about* (the nature of) models can be integrated productively. Chosen aims, concepts, reasoning skills and emerging motives develop in mutual relation as 'naturally' as possible. And though many details of this structure can be rightfully criticised, for instance whether we should choose for the behaviour of gases or of materials to start with, I would conjecture that, given the chosen aims and teaching approach, its overall pattern is much more robust to criticism. Such structures depict, in shorthand, possible and fruitful ways of dealing with known problems in teaching a topic. But they should always be interpreted in relation to much more detailed teaching-learning *scenario's* – another term that has encountered much opposition, as a scenario has often been misinterpreted as a single prescribed way of teaching X.

The development of problem-posing teaching of this kind has turned out to be a surprisingly difficult activity, both to design and to put into practice (Lijnse, 2005). So most colleagues think that our approach has failed. However, the principal point is whether the basic idea behind the problem-posing approach makes sense. If it does, we cannot simply let it go. Then it only means that we as designers (and teachers) have to try harder. As Laurence Viennot has written, coherence for pupils is often disturbed because of critical details that are simply overlooked by teachers and textbook writers. Or, in other words, the devil is often in the details. Once you have put on the spectacles of looking for such coherence, from the pupils' perspective, in textbooks and teaching processes, it is quite astonishing how many inconsistencies and gaps you discover. Mostly, good pupils are able to figure out the trouble these cause for themselves (in fact, that is why they are good pupils), but less able pupils often cannot, and get lost somewhere.

Our design experiments are in the first place meant to contribute to an experience-based extension of the body of didactical knowledge and not to direct implementation more broadly in teaching practice. This theoretical contribution takes place at two levels, first and foremost at the level of teaching X's, but by suitable reflection also at the level of more general didactical issues that might also apply to other topics. Such as: can we say something about the characteristics of suitable advance organisers, about how to induce a proper orientation, about what is a productive seed and how to introduce it, about how to organise a disciplined reflection

Models of Nature	**Motives**	**Nature of Models**
Global orientation on something like 'structure of matter'		as a topic of scientific interest and progress, in terms of deeper understanding (part-whole)
	should result in a feeling that this could be an interesting field of study, asking for a theoretical orientation	
that starts by narrowing down the field to macro knowledge of gases		
and the introduction of an initial kinetic model, that is initially plausible because it is intelligible and seems fruitful		
involving students in a disciplined modelling process, that leads to a further development of the model with an increased plausibility		
	but also to questions about its fruitfulness	
		that are answered by reflection on the properties and existence of particles and on particle explanations
	from which a suspicion about a fruitful 'research programme' should result	
that is explored by a further development of the gas model and its applications to the behaviour of liquids and solids as well		
	leading to a point of closure at which we may ask: 'what have we done?'	
		that is answered by reflection on the process of modelling in relation to 'how scientists work'
	resulting in an outlook on subsequent modelling	

that may lead to a new emerging motive, about how to productively integrate the teaching of science and of the nature of science, about how to productively round off a teaching sequence, and so on? And we have also found a more general pattern of teaching phases in our teaching sequences, that may be of some prescriptive value for the design of other sequences (Lijnse & Klaassen, 2004).

In the literature (e.g. Cobb *et al*., 2003), it is said that design research could result in the formulation of humble theories, although this term is not made very specific. In my opinion such humble theories should consist of a number of interrelated aspects. They should:

- start with problem identification, e.g. by analysis of current practice, supported by relevant diagnostic research results;
- describe possible aims in relation to views on teaching and learning;
- deal with conceptual analyses of the scientific subject matter;
- describe didactical phenomenologies and common-sense reasoning;
- describe and justify hypothetical learning trajectories;
- describe viable (research-based) didactical structures together with possible teaching-learning scenarios, including theoretical justifications and empirical outcomes as well as discussions of advantages and disadvantages, possible variations, didactical difficulties and ways out.

It is my conviction that such theories, if you could agree to call this a theory, could provide an important research-based contribution to the didactical expertise of teachers and curriculum developers.

Returning to our own experience, as far as the use of scenarios and didactical structures is concerned I have to admit that so far, except for some trial-school teachers, we have not yet succeeded in convincing many of them. Or maybe I should say any of them. Partly and mainly because such ideas seem to be too far from the regular concerns of teachers, of which the problem of insight is not a part. To put it in fashionable terms: they feel no sense of urgency as regards this problem, and do not regard themselves as problem owners. But also, partly, because, for the reason I mentioned before, we have not tried hard enough.

It is quite understandable that teachers have a lot of other, and from their point of view more urgent, concerns as *they also* have to survive the system, but that does not mean that the problem of insight is unimportant.

And as I have already said, as regards our approach, we have also not been able to convince many of our colleagues. Or even worse, for when I talked about a didactical structure for teaching modelling, Jon Ogborn gave it a fatal blow, by saying that I tried to make my theory run, while it was, as yet, hardly able to stumble. I have to admit that when I heard him utter precisely the same criticism about someone else's theory, I found it rather amusing. But this time it was less funny. Of course, as always, Jon was right, though he seemed to have forgotten that before you even can stumble at all, you must have made at least one step forward.

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Final remark

This brings me to the end of my talk. Maybe I could best summarise my work by paraphrasing a favourite saying of mine:

> I have done much in my life that was good and new;
> however, most of the good wasn't new,
> and most of the new wasn't good.

Fortunately, this leaves open the logical possibility that some tiny bit could have been both, but that is not for me to decide. Working in physics education has been quite interesting, but also often quite frustrating. I often had the idea that we are just walking in circles, that little progress is made, that new generations just redo the work of former generations, often without even being aware of it, just using a different terminology based on 'new' grand theories. Much research that is done, including my own, has little more than anecdotal value and sometimes not even that. Nevertheless, most of the time, it has given me great pleasure, particularly also because of the people that I had the privilege to meet and to work with. Some of them are present here, and I want to thank you all for taking me sometimes more seriously than I deserved. I will not mention any specific name now, apart from the most important one, Yvonne, my late wife. After my inaugural lecture in 1992, she felt rather disappointed because I had not explicitly thanked her in public for all the support she had given me. So let me use this final opportunity to make up for that omission. If I have done anything worthwhile during my career, it was only because she provided the solid foundation in my life, without which, as it has become clear since her death, working would not have possible at all for me.

Let me close by citing a part of one of my favourite songs, sung by a former Dutch pop-group: *The Cats*.

The End of the Show[8]
I'd like to thank you, yes, I do
I've got to face the truth
You've done the best you could to please me

I enjoyed it quite a bit
But I really must admit
That it could have been better all the time

This must be the end of the show
I hate to see you go
But it's all over now

Yeah, but it's all over now

[8] http://www.123video.nl/playvideos.asp?MovieID=41291

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6

'Developmental research' as a way to an empirically based 'didactical structure' of science[1]

Abstract

In recent decades, much work has been done in science education on large-scale curriculum development, ranging from a 'structure-of-the-discipline' approach to STS. At the same time, research on students' ideas has drawn attention to the underestimated problems of learning and teaching, which may largely explain the limited success of the curriculum efforts as far as cognitive learning is concerned. 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'. In contrast to this, I will argue that 'developmental research' is needed in which small-scale curriculum development is cyclically coupled to in-depth classroom research on teaching-learning processes. Such research should result in worked out examples of successful ways of teaching, based on new conceptual curriculum structures. Designing such 'didactical structures' constitutes a longer term research programme, which asks for international exchange and cooperation.

Introduction

Since the 1950s extensive work has been done on improving science 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 on 'discovery learning'; on Piagetian theory and stages of cognitive development; and last, on so-called science-technology-society (STS) education (Eijkelhof & Kortland, 1988; Yager, 1992).

Much later curriculum work started as a reaction to earlier developed curricula (of which PSSC and Nuffield O-Level were very influential examples) that were considered not to be suitable 'for all students'. In The Netherlands, for example, the PLON project has therefore made quite an effort in developing STS curricula at the secondary level. Its main rationale can be briefly characterised as 'physics for all, by promoting activity-based teaching and learning in relevant life-world contexts' (Lijnse *et al.*, 1990; Eijkelhof & Kortland, 1988). From such teaching, it was expected, on the one hand, that students would experience the content taught as more relevant. On the other, that they would be better able to understand and connect the

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[1] This chapter is a slightly edited version of the original publication in *Science Education 79*(2), 1995, pp.189-199. Copyright 1995, John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc. This original publication was a revised version of the following publication in French: Lijnse, P.L. (1994). La 'recherche-developpement': Une voie vers une 'structure didactique' de la physique empiriquement fondée. *Didaskalia 3*, 93-108.

concepts learned to their out-of-school world. Evaluation research has shown the first assumption to be reasonable, the second however has not appeared to be so simple (Wierstra, 1990). This is one illustration of my more general feeling that the curriculum effort, so far, has not (yet) resulted in much real progress, as far as insightful learning of science is concerned.

In the meantime, research in science education, as a second major branch of activity, has resulted in numerous studies that have drawn attention to the importance of topics like 'alternative frameworks', problem solving, and meta-cognition. These outcomes may, at least partly, explain why past curriculum efforts have been only moderately successful. And that, apparently, we still need to find better ways of teaching science.

Now, one could argue that such better ways could best be derived from the application of research results to practice. However, as much research on science education is theoretically embedded in a cognitive science perspective, as well as in modern philosophies of knowledge, its outcome is largely in terms of more general strategies and theories. This could explain why complaints about a theory-practice gap are as serious as they are long-lasting (Wright, 1993). Therefore, additional research is needed, as will be described in this article, that starts from a more content-specific framework. This takes 'improving science education', at a very concrete level, as the main aim of science education research. In view of the literature, it would seem that such an aim can be taken for granted. Our 'theories' should, in the first place, not so much aim to contribute to general ideas about teaching and learning, though we may and should draw on them, but to understand and improve science teaching practice.

1 'Top-down' instruction

Looking more closely at 'traditional' science curricula, one could say that in general the concepts taught are the basic concepts of science. The sequence in which they are taught reflects its basic 'logical' structure. The situations in which these concepts are to be applied are the usual paradigmatic idealised situations. It is precisely this latter aspect that STS curricula seek to change, by teaching in real-life contexts, leaving, however, in general, the conceptual structure and sequencing essentially unchanged. Apart from the fact that, because of the complexity of real situations, some new concepts may have to be added (e.g., PLON, 1986; de Jong *et al*., 1990).

In both traditional and most STS curricula teaching starts directly from, and focuses on, the perspective of science; that is, teaching science without really taking into account what students already know, think, and are interested in and what is relevant for the contexts of concern. The strategy thus aims at a direct 'top-down' transmission of concepts, even though the way in which this is done may include lots of 'discussions' and 'discovery' activities. In both types of curricula, such teaching almost unavoidably results in a process of forced concept development, which explains the apparent lack of differences in cognitive learning outcomes noted above (Wierstra, 1990).

As already mentioned, much research has shown that students' conceptual pre-knowledge needs to receive more instructional attention. Therefore, it is argued that learning should be seen as a process of conceptual change rather than of conceptual transmission. In STS teaching, students' common-sense ideas play an even more problematic role than in traditional teaching. Teaching science in everyday life contexts not only suffers from the unavoidable complexities of such contexts, it also requires that conceptual problems, related to differences between common-sense knowledge and science, can no longer be avoided. Moreover, students also appear to have common-sense ideas about the contexts themselves, to which they have to apply the knowledge to be learned. It is this latter type of pre-knowledge that explains why, even if we succeeded reasonably well in teaching correct conceptual knowledge, it might still not be used in real-life situations, as we found, for example, in our research on the teaching of radioactivity from a risk perspective (Eijkelhof, 1990; Eijkelhof & Lijnse, 1992).

2 Conceptual change as improved 'top-down' teaching?

We may agree with many others on the necessity of improved teaching strategies that take students' pre-knowledge into account. This reflects the adoption of (at least) a 'trivial constructivist' (von Glasersfeld, 1989) perspective, which is implied in statements like 'meaning is constructed' and 'concepts cannot be transferred from teachers to pupils' (Duit *et al*., 1992), and so on. Taking 'trivial constructivism' seriously means an important change of perspective, that is not at all trivial from an educational point of view. It is difficult to put into practice, precisely because it does not say very much about how to teach. The phrase, "the teacher must have a good idea of what concepts the pupils might already have and then engage pupils in activities that would help them construct the desired understanding" (Duit *et al*., 1992), places too much of the essential burden on teacher and students, and too little on the researcher. Freudenthal (1991), in a comment on 'constructivism', writes:

> "If 'constructivism' is to mean anything didactical, it must indicate […] 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. […] Lacking a convincing context, such terms as construction, reconstruction and constructivism are doomed to remain slogans. The only context that counts didactically is instruction itself, that is, instruction developed from the direction of the design onwards towards its realisation."

This points 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', that is, the view that students (or people) 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' so far 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 greater extent, to conflict strategies (Nussbaum & Novick, 1982) or to the CLISP approach described by Driver and Oldham (1986). So we do not agree with Scott *et al*. (1992) when, in describing three teaching routes, they say: "Each of these routes attempts to make links between pupils' 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 characterised as using new strategies to improve top-down teaching.

In my view, a more radical change is needed. If we want students to really understand and use what they are taught, we should engage with them in a 'bottom-up' learning process. In line with Freudenthal's view, we could say that we should not teach the concepts of science (as a product), not even in the constructivist manner outlined above, but guide students in the activity of 'scientificalising' their world. This might be done by carefully designing teaching tasks on the basis of a deep understanding of students' pre-knowledge and of its development in relation to the teaching tasks set. This entails a tension between 'guidance from above' and 'freedom from below' that can only be carefully regulated empirically. The design of such teaching is therefore necessarily an empirical process of closely interconnected research and development, that we call 'developmental research'. It concerns a cyclical process of theoretical reflection, conceptual analysis, small-scale curriculum development, and classroom research on the interaction of teaching and learning processes. The final, empirically based, description and justification of these interrelated processes and activities constitutes what we call a possible 'didactical structure' for the topic under consideration. The term 'didactical' is a translation of a word that is well known in many European languages. It should not be confused with the negative meaning of the English 'didactic teaching'.

3 Considering insightful science learning as a productive communication process

In developing such structures, a major focus is on studying the language and actions of students and teachers in interactive teaching situations. This unavoidably poses the ‘problem of interpretation’ (Klaassen, 1994b). This problem, however, is often not properly dealt with. The conclusion, for example, that, from a physicist’s point of view, students have many misconceptions and that they reason inconsistently across contexts, though both common in the ‘conceptual change’ literature, we consider to be often inadequate. In general, such conclusions are not based on a proper interpretation of what students are saying, but only point at what they are not saying, that is, correct science. To be able to build on students’ knowledge, and to use their constructions productively, we should first know what they really mean when they say what they say.

Klaassen (l994a) has drawn attention to this problem. He argues that proper interpretation should be at the centre of science (indeed, all) teaching, and that much literature on students’ ideas is guilty of misinterpreting them. The problem of interpretation is to explain how we are able to understand one another, given the nature of the evidence we have to go on. Klaassen’s (1994a, 1994b) reasoning, which I will briefly follow here, is based on Davidson (1990), a well-known philosopher of language, who argues that the smallest unit in which the problem of interpretation can be solved is a *triangle,* two vertices of which are communicators that are aware of the triangle, whilst the third is the communicators’ shared world of objects and events, the properties and existence of which are independent of the communicators’ thoughts. A necessary requirement for interpersonal understanding, that we as interpreters have to meet is that, in order to make the interpreted person’s behaviour intelligible to us, we must describe his actions and what he believes and wants in such a way that, as described, we can see for ourselves that what he did was the reasonable thing to do for him. So, one requirement is that we impose conditions of coherence and consistency on the pattern of beliefs, desires, intentions, actions, and so on, that we attribute to him. In order to give content to particular thoughts, there is another requirement that we have to meet. It is based on the obvious idea that, in the most basic cases, thoughts are about the sorts of objects and events that cause them. These two requirements, the complex interplay of which enables us to understand one another, might be summarised as follows: in order to make someone make sense, we must interpret him so that he comes out as largely consistent, a believer of truths, and a lover of the good (all by our own lights). This constitutes, in summary form, Davidson’s *principle of charity,* which Klaassen advocates as a necessary guideline for the interpretation of students’ thinking as well as for the construction of ‘good teaching’. All interpretation depends on our ability to find common ground.

One of the consequences of this principle is that we should not interpret students’ utterances at the ‘atomic’ level, but that we should try to find a coherent and sensible pattern in as many utterances as possible (this is almost the opposite of what happens in most questionnaire research on ‘misconceptions’). Starting from the fact that, basically, we are living in the same world as our students, we may conclude that as long as we do not yet have the feeling that, under the circumstances, what they say is sensible, we do not yet understand what they are saying.

This view is rather at odds with many constructivists’ interpretations of students' ideas, and with its radical branch in particular. Grandy and Hamilton (1993), for example, write about student-theories as follows: "Of course, these theories are often incomplete, incoherent and misguided." Much attention has been given to the individual process of knowledge construction, leaving the essentially social nature of communication and interpretation largely hidden. However, if science teaching deals with coming to understand public cultural knowledge in a social setting, research should not focus so strongly on aspects of individuality and idiosyncrasy in knowledge construction, but rather on its essential aspects of communality.

Realising that students' common-sense belief systems 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 science learning as learning to speak in a partly new way about the common world we live in implies that science can be learned meaningfully only if students engage in a gradual and social process in which mutual understanding is constantly secured. Freudenthal (1991) describes this as extending, systematising, and organising students' experiences so that they become 'common-sense of higher and higher order'. It means that the seeming discontinuity between scientific knowledge and reasoning, and common-sense knowledge and reasoning (Reif & Larkin, 1991), should be seen as differences between endpoints on a scale. It does not mean that the connection cannot be made 'continuously' (whatever that may mean).

So, if the teacher speaks in the language of science, even though expressing it in the most simple terms, he cannot immediately be understood as he intends by students who do not yet know that language (see, for example, Lijnse, 1992). This is the very characteristic of what is described above as top-down teaching. The result is verbalism, misconceptions and insufficiently applicable knowledge. It means, in my view, that the usual complaints about misconceptions and their 'resistance to change' should not so much be judged a consequence of students' 'alternative frameworks' as of 'bad' teaching.

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 to talk about events. The study of learning science should thus focus on this social process, and how to regulate it in such a way that it remains rooted in mutual understanding. Understanding such communication is therefore the key to understanding teaching and learning. It means, among other things, that the learning processes of both students and teachers should be studied in relation to each other. Studies of an individual's conceptual development (Scott, 1992; Niedderer & Goldberg, 1993) largely miss this essential focus on what teaching and learning science is all about. The essential interconnectedness of teaching and learning seems precisely to be absent in, for example, 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). This focus on what 'is in the mind' (Niedderer & Goldberg, 1993) seems to have its origin in cognitive science research. However, as will be clear from the above, in my view, science education research should take a different route.

4 Some further aspects of designing didactical structures

Though the principle of charity may be a necessary point of view for constructing teachable didactical structures, it does not, of course, provide any concrete directives for such construction. Some further interrelated aspects of designing didactical structures are outlined briefly below.

Aims and objectives

Designing instruction, and studies of learning and teaching processes cannot be separated from an underlying view on (science) education. For example, in our work, we still place much emphasis on 'science in context', or in STS terminology, on personal and social relevance of curriculum content. In modern words, this entails that the viewpoint of 'situated cognition' should be worked out further, both as a starting and end point for teaching. However, whatever the appropriate aims and objectives may turn out to be, their value should also derive from a developmental research process and cannot simply be decided on in advance.

Motivation

This aspect asks not only that we deal 'globally' with the interests of students, as STS curricula try to do, but also 'locally'. Activities should be designed such that students' own constructions, questions, and motivations largely guide the teacher (and designer). Such teaching can only take place in open learning situations in which the teacher's task is to problematise topics and arouse students' questions, let them think about possible hypotheses or answers, let them design ways to test their hypotheses, to give appropriate information and feedback, and so on.

Concept development

This aspect is at the heart of the matter. A basic pattern for a global outline of non-forced teaching can be described as following three successive periods (ten Voorde, 1977, 1990; Klaassen, 1994b) that presuppose one another: (1) a period of attention selection, in which a *ground level* for the following descriptive level originates; (2) a period in which a transition from ground level to a *descriptive level* takes place; and (3) a period in which, if necessary, a transition from a descriptive level to a *theoretical level* is made.

Meta-cognition

Part of a meta-cognitive perspective is that teaching should be largely problem posing instead of problem solving. This means that instead of making students look back and reflect *on* their ideas and opinions in order to replace them, which is a common recommendation, the challenge of a 'bottom-up' approach is to make students look forward and reflect *with what they already know* in order to extend it, by letting them largely frame for themselves the problems that drive their learning process. Thus a more positive awareness of one's own learning process, attitudes, and skills may be developed.

Learning of teachers

It is essential to focus not only on students' learning, but also on teachers' learning (of science and didactics), in direct relation to each other. We should not only start with students' ideas about the world, but also with teachers' ideas about teaching and learning. To prevent a practice-theory gap, it seems to be necessary that, in addition to having available concrete curriculum materials for students, both learning processes are studied together, reflected on and reported in pre- and in-service materials for teachers.

Curriculum structure

As the disciplinary structure of science is not the most suitable starting point for instructional design, we suggest that developmental research should in the long run lead to an empirically supported didactical structure for teaching the whole of science: an empirical description of a teachable longitudinal conceptual development of major interlinked learning strands, such as 'structure of matter', 'causes and processes', 'symmetries and conservation laws', 'mathematising and modelling', and so on. Such a goal also asks for a deep reflection on the concepts, structure, history, and aims of science.

Didactical theory

A detailed description of possible didactical structures for a certain topic may be presented in what we call a scenario. A scenario describes and justifies in considerable detail the learning tasks and their interrelations, and the actions which the students and teacher are supposed and expected to perform. It can be seen as a description and theoretical justification of a hypothetical interrelated learning and teaching process. In trying it out and closely monitoring it, it can be put to the test, and consequently revised. In the end, the scenario can be regarded as a rather detailed domain-specific theory of the teaching of a particular topic. Reflection on scenarios for various topics may lead to 'higher-level' theories.

Research methodology

Developmental research makes use of a large range of research methods. In the first stages, emphasis is mainly on the use of interpretative qualitative methods, which include introspection, interviews, classroom observation, protocol analysis of learning processes, historical analysis of concept development, and content analysis – in general, whatever method that may be useful to get insight into problems of teaching and learning and ideas about how to solve them. In later stages, more quantitative methods may be used as well.

The scenario serves as a description and justification of teaching methods and results, describing and analysing them in such depth that it is convincing in itself. The intent is not to 'prove' anything, but to make it possible for others to judge what has been done and to enable them to 'reconstruct' for themselves the processes described.

Dissemination and implementation

Though such scenarios will certainly not be sufficient to solve the usual problem of implementation, by being rooted in classroom research and development, they have the great potential advantage of being aimed at bridging the theory-practice gap at a very concrete level. In fact, as Freudenthal (1991) argues, the term 'implementation of results' is not an adequate description in the case of developmental research. It asks much more for a gradual and continuous process of dissemination, use, reflection, and further development of ideas, in order to establish change at all levels.

Values

As all education is based on values, the design of teachable didactical structures asks for an explicit embedding in what could be called a 'total view' of science education. That means an integrated view on the nature of teaching and learning, the nature and content of science, the nature and aims of education in general, and of science education in particular.

5 Conclusion

In this article, I have argued for 'developmental research' as a coherent way both to improve science teaching, and to make progress toward didactical theory. As such, this could be considered a long-term research programme. My plea stems from dissatisfaction with much present research in (science) education. Most educational research cannot, because of its general scope, but result in a theory-practice gap as regards its application. As soon as 'theories' have to be put into practice, everybody is, to a large extent, inventing once again his or her own wheel. Under the same theoretical heading, large differences in practice are constructed. To avoid that problem, in the work at Utrecht we aim for a detailed description, justification, and understanding of content-specific teaching and learning activities and processes. In working along these lines, of course we have to integrate more general ideas with content-specific ones, as both have their role to play. However, we would like to stress that if *science educators* (in cooperation with teachers) do not focus on developing content-specific theory, nobody else can or will, nor will anybody else be able to put general theory of whatever kind into practice.

Unfortunately, precisely because of the characteristics described above, developmental research is not (yet?) considered to be proper research – if we take the international science education research literature as a guide. If, as a research community, we do not succeed in exchanging views and experiences concerning the construction and description of actual teaching-learning activities and processes at a more concrete level, real progress in our field will remain strongly inhibited, and restricted to the exchange of theoretical rhetoric.

Developmental research combines, as has already been said, the practical with the theoretical, the learning of students with the learning of teachers, the aims of science teaching with their pedagogy necessary to achieve them. It is not aimed at building 'grand theories', such as, for example, understanding the human mind, but at understanding and developing 'good teaching practice'. It may be a way of working that is more realistic in its aims, though at the same time entailing that a large effort be made – much too large, in fact, to be done by a few people only, and thus requiring international cooperation at a very concrete level.

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7 Interpreting students' and teachers' discourse in science classes: An underestimated problem?[1]

Abstract

This chapter deals with the problem of the proper interpretation of discourse between students and teachers in classrooms. First, several interpretations of a concrete classroom protocol dealing with the paradigmatic case of static forces are discussed: an 'ordinary' teacher's analysis, an analysis in terms of misconceptions, and an analysis in terms of alternative conceptions. Though they represent common ideas from the literature, it is argued that these analyses all in some way misinterpret the discourse. By drawing on Davidson's principle of charity and by distinguishing between belief and meaning, we present an analysis that in our opinion interprets the discourse correctly. Its consequences for teaching are discussed, as well as its foundation in Davidson's philosophy.

Introduction

The mainstream of present research in science education focuses on students' ideas about natural phenomena and on the relation of such ideas to scientific concepts and theories (Pfundt & Duit, 1994). It is done by studying written responses on questionnaires, transcripts of interviews or classroom discourse, and so on. Numerous studies have pointed to the conclusion that students' ideas are often insufficiently taken into account by teachers and textbooks. It is also argued that this might at least partially explain the often very poor learning outcomes of science education as far as real insight is concerned. To improve matters, many researchers have nowadays adopted the constructivist stance that knowledge is personally and/or socially constructed on the basis of existing knowledge, and have begun to study individual and social learning processes to clarify *how* knowledge is constructed in science classrooms (Duit *et al*., 1992). In our own work, we focus on the interaction of teaching and learning processes. It is our experience that it is often difficult to interpret classroom discourse, let alone interpret it unambiguously. Adopting the constructivist stance has not helped us in overcoming these difficulties, as it only implies that knowledge is personally and/or socially constructed on the basis of existing knowledge (Driver *et al*., 1994). It does not throw light on the question of *which* new knowledge will be constructed on the basis of *which* existing knowledge. And it leaves unanswered the problem of how to properly and reliably interpret what has been constructed, both before and during education. Also, Lemke's (1990) sugges-

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tion to uncover 'thematic patterns' in classroom discourse, useful as it may be, takes for granted that a prior interpretative problem, namely, what students and teachers mean by their words and how they understand each other's words, has already been solved.

In our opinion, this methodological problem of how to correctly interpret students' and/or teachers' utterances, be it as answers to questionnaires or as transcripts of classroom discourse, needs more attention. To discuss this problem further, both theoretically and methodologically, we think it appropriate to start with a concrete example of a classroom discourse. As such, this example is not meant to represent a piece of empirical research, but only to provide a concrete base from which our theoretical and methodological position will gradually be unfolded. Therefore, in the second section, we analyse this discourse according to how we interpret current positions in the literature. Then, in the third section, we point to some deficiencies in those analyses, which involve at the same time a critique of the underlying positions. Subsequently we present our own analysis and compare it to the previous ones. We will thereby have elaborated our theoretical position at a concrete level. In the fourth section, we discuss and compare some of the consequences that the various analyses have for teaching. In the final section, we justify our own analysis theoretically by drawing on Davidson's philosophy (1980, 1984, 1990).

1 A concrete example of a classroom discourse

The example with which we will illustrate our line of reasoning is taken from a series of lessons on mechanics.[2] One reason this example has been chosen is that it deals with the paradigmatic book-on-the-table situation, which shows up in one form or another in many publications (Minstrell, 1982; McDermott, 1985; Clement, 1993), so comparisons with the literature can readily be made.[3] Another, more important reason is that we consider it to be a representative example of communication problems as they occur in classrooms. As a consequence, it allows us to illustrate our view on the problem of interpretation in an ecological setting. We hope that just this one example will serve this purpose.

In the previous lesson, the students watched a specially developed video about

[2] Though it is not relevant to our line of reasoning, the following may serve as some further background information. The series of lessons took place in the fourth grade (16+) of a secondary school in which the PLON curriculum is used (Lijnse *et al.*, 1990). In this curriculum, mechanics is taught in the context of traffic situations. The lessons were closely monitored by an observer to follow and study as closely as possible the teaching-learning processes that took place. The observer made notes about all relevant activities. Discussions between teacher and pupils were videotaped and within groups of pupils audio-taped and subsequently transcribed. The chosen protocol is such a transcription.

[3] It is perhaps noteworthy at the outset that it is not our intention to solve the book-on-the-table problem as it is conceived in the literature. According to us, there simply is no such problem (cf. the fourth section).

forces that act when cycling. The following transcript begins with the teacher, who intends to summarise and elaborate on the video by means of the well-known air track. His introductory question, in which he asks for the forces acting on the glider when it rests on the not-yet-operating track, is meant simply to remind the students of the supposedly well-known static forces that are acting in that situation. Then the following discussion occurred, which took about twenty minutes.

1	Teacher:	The video has been about forces that act when cycling. Well, here [points to the glider on the track] I have a kind of bicycle. Let me now first ask what forces are acting on it. Just try: What forces do you think are acting at this moment? Are there any forces acting?
2	Eric:	Gravity.
3	Teacher:	Gravity, Eric says. What if gravity were the only force, what would happen then?
4	Eric:	Then it would go down.
5	Teacher:	Then it would go down. Ernie, what other forces could be acting?
6	Ernie:	Eh … well …
7	Teacher:	What prevents it from falling down?
8	Ernie:	The track.
9	Teacher:	Right, the track. So the track has to supply a counterforce to prevent the glider from falling down. Just for the sake of completeness: Eric, which direction has gravity?
10	?:	[joking] Upwards.
11	Eric:	No, downwards.
12	Teacher:	So, Orson, the force of the track is upwards. Right?
13	Jane:	How’s that?
14	Orson:	Well, otherwise it would fall down.
15	Teacher:	Otherwise it would fall down, he says. So, if it did not rest on the track and I dropped it, then only gravity would act and it would fall down. If the track wants to stop it, then it will have to push the glider upward.
16	Jane:	But the track does not push, does it?
17	Teacher:	The track does not push.
18	Jane:	No …
19	Orson:	Well, the track is just there.
20	Jane:	… It’s just there.
21		[Some students are mumbling things such as, “Don’t make such a fuss. Just accept it.”]
22	Teacher:	If you drop it, it will fall down; a force will act upon it.
23	Jane:	Sure, if the track is not there.
24	Teacher:	Okay. If you put it on your fingers … I can’t take it off. [The teacher cannot get the glider off the track, and takes a small weight instead.] It’s the same with this thing [the weight], isn’t it? If you drop it, it will fall down. Now I want to stop it [places the weight on the tips of his fingers]. Since it is such a small weight, you don’t feel much. But if you put a heavy weight on your fingers, you will feel it.
25	Jane:	Okay.
26	Teacher:	That is because you will have to exert a counter pressure. So you do have to …
27	Jane:	Sure, if you’re doing that yourself.
28	Teacher:	If I place a heavy weight here, then my fingers will go down. If I want to keep it in place, I will have to push it upward. The track will do that too, it’s just that we don’t notice that. We don’t notice that the track does it, the track doesn’t move …
29	Carl:	Yes, but the track can’t push upward, can it?

30	Teacher:	… But the track in fact does it as well.
31	Carl:	Yes, but the track can’t do that, can it?
32	Teacher:	Oh yes, it can do just that.
33	Carl:	You can push upward with your fingers, but the track can’t.
34	Teacher:	Let me take something else, something more flexible than metal. [Fetches a piece of foam rubber and puts it in front of him.] Here goes. So I will now try to convince you that the track really exerts an upward force. That is, I agreed with Orson, Jane did not; let’s see whether we can come to an agreement. [Puts the small weight on the foam rubber, which gets pushed in a bit.] If I put this thing here, the foam rubber gets pushed in, doesn’t it? Well, actually I need something a bit heavier …
35	Jane:	Oh well, I do believe you as it is.
36	Teacher:	Do you? So you do actually believe that. [Laughter.] So, the foam rubber will get pushed in if you put something heavy on it. And if we don’t put something heavy on it, but push it in and let go [does so with a finger], what will happen then?
37	Jane:	Then it will come up again.
38	Teacher:	Then it will come up again? Why’s that?
39	Jane:	Well, because there’s nothing on it.
40	Teacher:	Sure, but what does it do then, when it comes up? Then it pushes upward, doesn’t it?
41	Jane:	What?
42	Teacher:	[Somewhat more pressing.] Then it pushes upward, doesn’t it?
43	Jane:	No, then it just gets back to its original state.
44		[Some students seem to suggest that Jane is just being stubborn.]
45	Jane:	No. I don’t think that has got anything to do with it.
46	Teacher:	Don’t you? I push the foam rubber in, put something on it, and the foam rubber pushes it upward. Then that is an upward force.
47	Jane:	Well, I think that’s really very strange.
48	Teacher:	Do you?
49	Jane:	Yes. That is not … well … no, that is not a force. I don’t think it is really a force.
50	Teacher:	If you want to push something up, then for that purpose you will have to exert a force. And now [pushes the weight into the foam rubber and then lets the foam rubber spring back] it is pushed in and it pushes the weight back up.
51	Jane:	Okay.
52	Teacher:	But you don’t think that’s a force.
53	Jane:	Right.
54	Teacher:	You don’t think that’s a force. For it is the same, isn’t it? And do you consider this to be a force, when it falls down?
55	Jane:	Sure, that’s gravity.
56	Teacher:	So, the downward motion is due to a force, but if it moves up [lets the weight again move up from the foam rubber] then that is not due to a force?
57	Jane:	Right.
58		[Laughter from the class. The teacher remains serious.]
59	Teacher:	What if I now … I throw it upward, like this.
60		[Jane also begins to laugh about the awkwardness of the whole situation.]
61	Teacher:	Is that a force or not?
62	Jane:	[Laughing.] It is, of your hand it is.
63	Teacher:	Of my hand it is. And now I let the foam rubber do it [again does so] and then it is no longer a force.
64	Jane:	[Still laughing a bit.] Right.
65	Teacher:	What, then, is the difference?

66	Jane:	[Serious again.] Well, that motion just goes all by itself. That's just the way things go. [Laughter.] Well, I really do think that's strange.
67	Teacher:	So, because it goes all by itself, that is why according to you it is no force. If it now of itself gives something a slap, then that would be a force.
68	Jane:	Yes.
69	Teacher:	I see. Well, so it seems that we haven't been making much progress. I think there will be a force if you push it in, and Jane still doesn't think that that is a force. I'll leave it at that for a while. For the time being, everybody may think about it as he wishes. I would like to know, however, what the others think about it.
70		[Of the others, most indicate that they agree with the teacher, while no one indicates agreement with Jane. Some students, including Orson and Carl, are in doubt.]
71	Teacher:	All right. Let's leave it at that for now. Perhaps I will be able to convince you later. According to me, the difference between the foam rubber and the metal is that it can't be noticed that, well, that the metal is springy. But the metal also has some spring that allows it to push back. So the metal is harder and – but now I speak for myself – it gets pushed in, but it does spring back and thus exerts a counterforce. Okay. It is sort of funny, though, that we still don't agree.

Before discussing this transcript in more detail, we first want to mention two points on which we hope everybody will agree. The first point concerns the situations in the context of which the discourse takes place. We detect seven such situations: the glider rests on the track (1)[4]; the weight falls down (24); the weight rests on the teacher's fingers (24); the piece of foam rubber is pushed in a bit by the weight (34); the foam rubber comes up again after it has been pushed in (36-38); the weight moves up after it has been pushed deeply into the foam rubber (50, 56, 63); and the weight is thrown upward by the teacher (59). The second point concerns the (very experienced and good) teacher: he is open-minded and takes his students seriously (17, 34, 56, 58, 67); he tries to react appropriately and improvises the best he can (24, 28, 34, 36, 63); he nevertheless fails to achieve what he wants and honestly admits that (69, 71). Now, how can we understand this transcript, and what can we learn from it?

2 Several analyses of the previous classroom discourse

The "ordinary" teacher's analysis[5]

We think that many ordinary teachers will recognise situations like the one described in this transcript from their daily practice and would analyse them more or less commonsensically as follows (see, e.g., Bell, 1994). The teacher is doing his

[4] Here, and in what follows, numbers between parentheses refer to the transcript.

[5] To prevent misunderstanding, this analysis represents our view of how, in general, an ordinary teacher who is not familiar with research on students' ideas could analyse and react to situations like the one represented in the protocol. It is not meant in any way to criticise teachers. In fact, this analysis and reaction seem to be quite sensible from the point of view of the practising teacher. It should also be noted that we do not mean the teacher in the transcript by 'the ordinary teacher'.

utmost to make himself clear to his students. In particular, he is doing everything he can to remove Jane's objections (24, 34, 46, 63, 71). Jane, however, keeps on uttering confused remarks (18-20, 39, 43, 66), probably because she does not yet understand Newton's laws well enough (15-16, 26-27).

In this analysis it may even be said that the teacher gives too much attention to Jane. The other students clearly indicate that Jane is just being a bore (21, 44, 58), probably because most of them have understood the teacher's explanation from the start (70). Perhaps Jane has not done her homework or has not paid close enough attention to the video in the previous lesson. At any rate, she had better do some extra studying to understand the teacher's explanation next time.

From the point of view of classroom management, teaching advice based on this analysis could be to give less attention to students like Jane. And by all means, if teachers want to convince students like Jane, the best advice would probably be to take them aside and explain Newton's laws precisely in some detail.

Analysis in terms of misconceptions

A somewhat different analysis consists in the statement that Jane has misconceptions, i.e., ideas that are in conflict with correct ideas of physics. Whereas she holds, or at least does not protest against, the correct idea that gravity acts downward on the glider at rest (1, 2, 9-11), she erroneously holds the idea that the track does not push (16). On the other hand, when a heavy weight is put on your fingers, she agrees that you will have to exert a counter pressure (24-27). Whereas she correctly holds that when the weight falls down, its downward motion is due to gravity acting upon it (54, 55), she has the misconception that when the weight moves up from the foam rubber, its upward motion is not due to a force exerted by the foam rubber (56, 57). She again correctly holds that when you throw the weight upward, its upward motion is due to a force exerted by your hand (59-62).

Thus, one may conclude the following: Jane knows about the existence of gravity, and that it acts downward on everything. In some apparent cases, such as a weight on one's fingers, she knows that a counterforce is needed; but in less apparent cases, such as the glider on the track and the weight on the foam rubber, she has the misconception that no counterforce is needed.

An analysis in terms of students having misconceptions is not uncommon. Especially during the first stage of the conceptual change research paradigm, many publications appeared in which all kinds of misconceptions were investigated, predominantly by means of questionnaires (Pfundt & Duit, 1994; McDermott, 1984; Halloun & Hestenes, 1985). In line with this, the transcript may also be seen as a kind of questionnaire consisting of seven items corresponding to the seven situations in the context of which the discourse takes place. Each item asks whether gravity or any other forces are acting. From Jane's answers to this questionnaire, one may also conclude, as is often done in such investigations, that we have one of the many examples of a student who reasons inconsistently and holds wrong epistemological commitments (Hewson, 1985), as she does not seem to be aware of the fact that the laws of physics are supposed to be generally valid (Finegold & Gorky, 1991).

One way to bring out the difference between the analysis of the ordinary teacher and an analysis in terms of misconceptions relates to the estimation of students such as Jane. Whereas in the former analysis Jane could be considered a student who has not paid close enough attention or is just being a bore, or for whom physics simply may be too difficult, in the latter analysis Jane is considered a student with an excellent attitude. In fact, it is the other students' attitude of just accepting what the teacher says (21) that must be considered detrimental to really insightful learning, because it is precisely this attitude that leads to the survival of misconceptions. After all, as may be safely conjectured on the basis of the research on misconceptions, many of the other students will hold the same misconceptions as Jane does.

Teaching advice based on analysis in terms of misconceptions would therefore be to challenge both Jane and the other students to bring their misconceptions forward. As Van Heuvelen (1991) put it: "Instead, students should become *active* participants during lectures in constructing concepts, in confronting preconceptions that are misconceptions, in reasoning qualitatively about physical processes, and in learning to use concepts to solve problems." Related advice is given, e.g., by McDermott (1984), who wrote: "Experience has shown that merely presenting the correct information, either orally or in written form, is seldom effective in helping students overcome misconceptions. Specific difficulties must be directly confronted and deliberately addressed." Labudde *et al*. (1988) noted that "new knowledge should be explicitly contrasted with prior knowledge in order to remove inconsistencies, to ensure the coherence of the students' new knowledge and to minimise interference from conflicting knowledge." Champagne *et al*. (1980) argued as follows: "We propose that instruction in classical mechanics can be improved by continuously encouraging students to reject an Aristotelian system of beliefs and to adopt a Newtonian paradigm. The main strategy of this approach, which acknowledges the pre-existing belief system of the students, is to compare and contrast the two paradigms." Therefore, from this perspective, real insight can only result from a combined process of learning correct ideas and *unlearning* misconceptions.

Analysis in terms of alternative conceptions

Yet another type of analysis maintains that Jane has ideas that are in conflict with accepted ideas of physics, but adds that it is not at all surprising that she has those ideas: "In some cases, prior knowledge acquired by informal learning or through cultural transmission of 'folk knowledge' is inconsistent with the formal knowledge to be acquired during schooling. This is particularly likely in the natural sciences, where prior experiences, though categorised as naive from a scientific perspective, provide reasonable explanations to guide daily behaviour" (Anderson, 1992). Researchers that adhere to this analysis prefer to call students' ideas *preconceptions* or *alternative conceptions* instead of *misconceptions,* because, as Dykstra *et al*. (1992) put it: "These *alternative* conceptions manifest themselves as *useful* common-sense beliefs about the world." Thus, instead of emphasising that from a scientific point of view students have incorrect ideas, they try to frame the alternative conceptions that students seem to live by in their daily life. Concerning students' ideas about force and motion, for instance, Gunstone and Watts (1985) framed intuitive rules such as: forces are to do with living things; if a body is not moving there is no force acting on it; if a body is moving there is a force acting on it in the direction of its motion, and so on. In relation to the problem at hand in our transcript, Clement (1993) formulated the "deep seated" alternative conception of "static objects as barriers that cannot exert forces."

With this analysis, one will interpret the transcript as showing such intuitive rules at work in Jane's reasoning. This interpretation then also requires the additional conclusion that students may reason inconsistently across contexts. For example, this rule associating force and direction of motion may be used by Jane in some situations, but not in her reasoning about the weight's upward motion from the foam rubber. This apparent lack of consistency is a matter of considerable debate. One often tries to make this additional conclusion plausible by noting that from an everyday life perspective, there is no need for coherence or general applicability across a wide range of situations. Sometimes it is simply taken for granted. Grandy and Hamilton (1992), for instance, wrote about students' theories: "Of course, these theories are often incomplete, incoherent and misguided." Champagne *et al*. (1980) wrote accordingly: "Their pre-instructional belief system has a loose structure, displays little interconnectedness, and lacks an overlying formalism. In consequence, the belief system is highly flexible and can accommodate new information locally without producing any conflict with other parts of the system." Others, however, have argued for the existence of more consistent patterns in students' alternative ways of reasoning (see, e.g., Viennot, 1985, 1994; Finegold & Gorsky, 1991; Engel Clough & Driver, 1986; Dykstra *et al*., 1992).

So far, this analysis has focused on only one side of the coin, i.e., on students' conceptions. In teaching, however, as the transcript shows, the interaction between teacher and students is essential. Focusing on this interaction from the perspective of alternative conceptions, the previous transcript can in some sense be viewed as a clash of two worlds, somewhat similar to the clashes of incommensurable world views that Kuhn (1970a) has written about, for example. On the one hand, Jane reasons from her frame of reference; on the other hand, the teacher uses the Newtonian concept of force. He reasons consistently from this Newtonian framework, because his knowledge and epistemological commitments are such that he knows that the laws and concepts of physics must be generally applicable across situations. One could say that the teacher and Jane are more or less living in different worlds. They do not see the same objects and events, because observation is theory-laden. In each world, different concepts are used, being part of different kinds of knowledge, with different characteristics and problem-solving procedures (Reif & Larkin, 1991).

With this analysis, it is quite understandable that Jane and the teacher do not understand each other and that the teaching process fails. Anderson (1992) wrote: "These well-entrenched alternative conceptions (or misconceptions from the viewpoint of the scientist) can have profound effects on the students' capacity to accept and internalise scientific explanations that may be contradictory to prior experience." Gunstone and Watts (1985) pointed to the importance of language in this respect: “The issue of language is difficult and complex. Students use language which is meaningful to students; teachers use language which is meaningful to teachers. There are a range of important teaching implications to be derived from an understanding of language and its role in learning.”

What students have to go through is a conceptual change – a change in world view, somewhat similar to a Kuhnian scientific revolution. A global teaching suggestion that all researchers who adopt this analysis therefore agree on is that one should take into account and be sensitive to students’ views of the world. In the fourth section, we will discuss the main procedures that those researchers have proposed to successfully “overcome the dominance of an alternative conception” (Clement, 1993).

3 Our own analysis

Some deficiencies in the previous analyses

Both the analysis of the ordinary teacher and the analysis in terms of misconceptions start from and end with the point of view of correct physics as the sole norm and perspective from which to talk about teaching. In both analyses the main conclusion is that Jane holds ideas that are in conflict with ideas that physicists have. We think this conclusion is premature. Of course, we agree that Jane does not yet know Newton’s laws, and that she says things that a physicist would not say, or at least not in those words. There would only be a conflict of ideas, however, if it is assumed that she uses and understands expressions containing the word *force* as a physicist uses and understands them. But is this the right way to interpret her use of such expressions?

A similar remark can be made concerning the analysis in terms of alternative conceptions. Jane is said to reason from an everyday life perspective from which there is no need for coherence or general applicability across a wide range of situations. However, from the way Jane argues, it seems clear that she herself does not experience any incoherence at all, even when she is clearly aware that the teacher explicitly tries to point out to her that she is being incoherent (56-65). In fact, her problem seems to be that she cannot understand that the teacher does not understand her obvious points (20, 43, 66). Is it therefore right to conclude that Jane reasons incoherently?

Both the analysis in terms of misconceptions and the one in terms of alternative conceptions point out that students’ ideas should be directly addressed. Some more specific strategies to stimulate conceptual change are also advocated. Students should be given the opportunity to express and discuss their ideas. The status of their alternative conceptions should be lowered, for instance, by means of conflict, bridging, or analogical situations. We note, however, that the teacher tries to do precisely these kinds of thing. He gives Jane the freedom to express herself (48, 52, 61), uses bridging situations and analogies (24, 28, 50-54, 71), and tries to address Jane’s ideas and to arouse a conflict (50, 54, 65). Yet he does not succeed. Why?

Global structure of the discourse between Jane and her teacher

Let us consider the transcript anew. The first thing to note is that the teacher analyses his discourse with Jane as their having a *difference of opinion* about whether "the track really exerts an upward force" (34, 69). Accordingly, he sees it as his aim to convince Jane that his opinion is the correct one (34, 71). He does so, not by arguing in terms of Newton's laws, as he probably quite rightly assumes this to be inappropriate at this stage, but by more or less ostensively and comparatively pointing at ever more clearly visible cases of acting forces. In the end, the teacher considers his attempt a failure: "I do think there will be a force if you push it in, and Jane *still* doesn't think that that is a force." (69). Given that this is how he evaluates the situation and that he probably cannot think of any other way to convince Jane, it is fair of him to state explicitly that for the time being, he will let the matter rest (69). He even emphasises: "It is sort of funny, though, that we still don't agree." (71).

Do the teacher and Jane really have a difference of opinion?

Is the teacher right in analysing his discourse with Jane as their having a difference of opinion? We do not think so. Of course, Jane agrees that the glider's being supported by the track is similar to the weight's being supported by the teacher's fingertips, in the sense that in both cases an object's falling down is prevented. Of course, Jane agrees that throwing a weight upward and letting the foam rubber do it are similar in the sense that in both cases the weight is made to move upward. And of course, the teacher agrees that the piece of foam rubber and the metal track cannot of themselves push something upward or give a slap in the way that we can (16, 29, 33, 67, 68), or that the foam rubber springs back without us having to do anything, that it goes all by itself (66). And without doubt, Jane could also come to agree with the teacher (perhaps along the lines suggested by Minstrell, 1982) that the metal track is like the piece of foam rubber in the sense that it is sort of springy too, but unlike metal in the sense that metal is harder and that its springiness cannot be observed that well (28, 71).

Thus, the teacher and Jane seem to *agree* on all the similarities and dissimilarities between the various situations. Moreover, toward the end of their discourse, the teacher seems able to sort of predict when Jane will say that a force is exerted and when not (56, 63, 67). Nevertheless, they have an ongoing and unresolved quarrel. If they were asked the question, "Does the track exert an upward force?" or "Does the foam rubber exert an upward force?", the teacher would answer yes and Jane would answer no (34, 71).

What is the source of the argument between Jane and her teacher?

This leads us to the following question: Is it possible that, on the one hand, there really is no difference of opinion between the teacher and Jane, while on the other, their discourse runs aground in a yes-no stalemate? To answer this question, we find it useful, like Gunstone and Watts (1985) to bring in the issue of language (though somewhat differently than they do it, cf. the next section). We do so by assuming that the teacher and Jane speak slightly different languages. In particular, we assume that the expression “to exert a force” does not have the same *meaning* for the teacher and Jane, i.e., that they do not use and understand that expression, or something like it, in the same way.[6] We think this is a reasonable assumption, given that the teacher uses the expression in a Newtonian way and Jane most likely does not yet know the Newtonian language.

Let us begin then by explaining how under this assumption their yes-no stalemate need not reflect that there is a *conflict of belief*, that they are having opposing beliefs about the world. That is, the teacher’s answering yes and Jane’s answering no to, for example, the question, “Does the foam rubber exert an upward force?”, need not reflect that they are making opposite claims concerning the occurrence of a particular kind of event. To explain this, we will have to make further assumptions about the (different) meanings that the teacher and Jane assign to the expression “to exert a force”. We will show that this can be done in such a way, that by uttering the (his) sentence, “The foam rubber exerts a force,” given the meaning he assigns to the expression, the teacher is rightly asserting the occurrence of a particular kind of event, while by uttering the (her) sentence, “The foam rubber does not exert a force,” given the meaning she assigns to the expression, Jane is rightly denying the occurrence of a (different) kind of event. Concerning the teacher, there is no problem here: by uttering his sentence, “The foam rubber does exert a force,” he is, given that he uses the expression in the Newtonian way, rightly asserting the occurrence of an event that would not have happened if the foam rubber had not been there (namely, the weight’s upward motion). But what about Jane? Can we also make an assumption concerning her use of the expression, such that in using it thus she is right in saying, “The foam rubber does not exert a force”?

To make a plausible assumption concerning Jane’s use, we simply make the *methodological* suggestion to assign such meaning to her expression “to exert a force”, that whenever she would answer yes (or no) to the question, “Does this exert a force?”, she is, according to us, right in doing so. Among the situations in the context of which the discourse takes place, there are two in which Jane answers yes: the teacher throws the weight upward; the teacher supports the weight. In the other

[6] Note that only the teacher actually uses the expression “to exert a force” (34, 50, 71). He also uses (we think as more or less synonymous with it) the expressions “to supply a force” (9) and “to be a force of” (12). Jane, too, uses the latter expression (62). In (63, 64) and (67, 68) their yes-no stalemate concerns an actual question of the form “Is this a force of ... ?” In (15, 16) and (42, 43) it concerns an actual question of the form “Does this push?” We think that for both Jane and the teacher, to push is a specific example of to exert a force. When henceforth we use the phrase “the expression ‘to exert a force’”, we intend it to be understood as “the actual expression that is used as a synonym to the expression ‘to exert a force’” (e.g., “to exert a force,” “to supply a force,” “to be a force of”). In the same vein, we intend a phrase such as “Jane’s assertion of her sentence ‘The track does not exert a force’” to be understood as, e.g., Jane’s answering no to an actual question of the form, “Is this a force of the track?” Furthermore, it is part of our assumption concerning the expression “to exert a force” that the expression “to push” does not have the same meaning for the teacher and Jane.

situations she answers no to the question, “Does this (the foam rubber, the track) exert a force?” We guess that she would also answer yes if, instead of the teacher, another living thing supported something or threw something upward, or if a living thing did something other than that (e.g., set another object in motion quite generally, give another object a slap, deformed another object, and so on). She even indicates that she would also answer yes in the event that an inanimate object of itself caused things these kinds of effect (67, 68). Accordingly, we suggest the following assumption: for Jane, the expression “... exerts a force” has application to an object precisely if an event occurs that the object of itself has caused, or if it is an object that could of itself cause something to happen to another object but instead merely supports it.[7]

If we interpret Jane in this way, we will agree with her that when the glider rests on the track, an utterance of her sentence “The track exerts a force” is not true, simply because the track could not of itself cause something to happen to the glider (e.g., throw it upward). Moreover, by uttering her sentence, “The foam rubber does not exert a force,” she is, according to the above interpretation, denying the occurrence of an event that the foam rubber of itself has caused. By her utterance she is not denying that the weight moves upward nor that the foam rubber has been involved in the weight’s upward motion, but only, and rightly so, that the foam rubber of itself has caused the weight’s upward motion. It is rather the teacher who, by pushing the weight deep down into the foam rubber and then letting the foam rubber get back to its original state (43), has in effect caused the weight’s upward motion. We thus conjecture that Jane would have answered yes if she were asked, “Does the teacher exert a force?” That is, if her answer had been yes, this would have counted in favour of our interpretation.

According to this analysis, the conflict that the teacher and Jane themselves think they are having (34, 69) is just an apparent one. If the teacher had known that Jane uses and understands the expression as indicated earlier, he would have assented to, for example, Jane’s utterance of “The track does not exert a force.” Their discourse runs aground in a yes-no stalemate, not because they really have a difference of opinion, but because both of them wrongly assume *identity of meaning* with respect to the expression.

Comparison of our analysis and the analysis in terms of alternative conceptions

According to our analysis, Jane does not reason incoherently at all. In fact, we have interpreted her in such a way that we can see her as applying her expression “to exert a force” consistently and rightly to the various situations in the context of which the discourse takes place. So not only does she not reason inconsistently, we also agree with what she believes.

[7] If the student in the discourse were still available, we could check this assumption and, if necessary, modify it. We would not check it by letting her judge this rather cumbersome, verbal formulation of it. We would ask her, in various circumstances: “Does this exert a force?”

We do not think of the discourse between the teacher and Jane as a clash of two conflicting world views. We rather think of it as a communicative failure. The source of the miscommunication is that the teacher and Jane think they are speaking in the same language, whereas in fact they are speaking different (though similar-sounding) languages. Because they are not aware of this, there is a sense in which the teacher and Jane may come to think of each other as living in different worlds. Indeed, both of them may have felt a gap between them or, as Ten Voorde (1990) called it, a 'gulf of ununderstandableness', without being able to bridge it. The teacher may have felt it as his being unable (despite all his efforts) to convince Jane. Jane may have felt it as the teacher's tireless attempts to convince her of something she just cannot believe: "I really do think that's strange." (47, 66).

In very much the same way, Ramberg (1989) argued that there is a sense in which Kuhn's statement that scientists operating within incommensurable paradigms practice their trades in different worlds can be understood. Ramberg did so by analysing the problematic notion of incommensurability, about which Kuhn himself (1970b) wrote: "In the transition from one theory to the next words change their meanings or conditions of applicability in subtle ways. Though most of the same signs are used before and after a revolution – e.g., force, mass, element, compound, cell – the way in which some of them attach to nature has somehow changed. Successive theories are thus, we say, incommensurable." Ramberg (1989) suggested not thinking of incommensurability as a relation between theories, world views, social practices, or paradigms, but as "a characteristic of the discourse that results when we proceed *as if* we are using the same vocabulary, and so interpret others by applying linguistic conventions to which they are not party" (p.132). Instead of saying that the teacher and Jane have incommensurable world views, we should rather say that their discourse is incommensurable. From Kuhn and others, we may learn that the discourse between scientists has often been, and often is, incommensurable. Indeed, the changes of meaning that are involved in the transition from one theory to the next may easily give rise to situations in which two scientists, like the teacher and Jane, are not aware that they do not use some of their words in the same way. As a result they may, like the teacher and Jane, experience sheer unsurmountable difficulties in their attempts to understand one another, even to the extent of giving up such attempts altogether. But whereas they may thus come to think of each other as living in different worlds, they may in fact, like the teacher and Jane, be only words apart. We thus also hope to have made it clear that we shy away from literal talk about different worlds, reality being relative to a conceptual scheme, comprehensive differences in world view, and so on.

Let us close this section by pointing out what we think is the difference between the way we have brought in the difficult and complex issue of language and the way Gunstone and Watts (1985) did so. They wrote: "Language which is meaningful to teachers may, because of students' views of the world, have a quite different (even conflicting) meaning for students. If we are not sensitive to this, we can unwittingly reinforce the very views we want to change."

We agree that language which is meaningful to a teacher may indeed have a different meaning for students. In fact, we have just argued that this is the case for

Jane and her teacher. However, this is *not* because they have *alternative beliefs about the world,* i.e., beliefs we would want to change (we interpret Gunstone and Watts' phrase "views of the world" as meaning beliefs about the world). According to us, there simply is no identity of meaning concerning some terms, because scientists have come to assign a rather specific meaning to them. So we would rather say that if one is not sensitive to this, one will unwittingly create apparent conflicts and talk at cross purposes (incommensurable discourse).

In our own analysis, we have not assumed or taken for granted that Jane has alternative beliefs. On the contrary, we have assumed that Jane's beliefs are quite alright and have thus come to assign a meaning to her expression "to exert a force." It can be said that instead of assuming identity of meaning we have rather assumed *identity of belief.* By doing so, i.e., by finding as much common ground with Jane as possible, we have interpreted her not as having different views or beliefs, but as speaking a different, although similar-sounding, language. Given that we are in agreement with her, that there is nothing wrong with her beliefs, we also see no need to change Jane's beliefs. We do see a need, of course, to make her (want to) add substantially to what she already knows.

Let us try to bring out the difference in yet another way. Although we think that Gunstone and Watts (1985) and Clement (1993) were aware that students do not use the word *force* or expressions containing it as a physicist does, in their formulations of students' intuitive rules or alternative conceptions they nevertheless use "force," e.g., students believe that static objects are barriers that cannot exert forces. What they thus leave unanswered is the question of which meanings students assign to expressions containing "force." In effect, they also leave unanswered the question of which beliefs are represented by the intuitive rules or conceptions as formulated by them.[8] We, on the other hand, have tried here to answer the question of which meaning Jane assigns to the expression "to exert a force." Her holding true her sentence "Static objects are barriers that cannot exert forces" accordingly represents her (correct) belief that static objects are barriers that cannot of themselves cause something to happen (e.g., set another object in motion or give it a slap).

We refer to Klaassen (1995) for an answer to the question of which meanings students assign to some other expressions containing "force," for an answer to the question of which beliefs of students are represented by the intuitive rules as formulated by Gunstone and Watts, and for a comparison of those beliefs to the "common-sense theory of motion" that Bliss and Ogborn (1993) presented.

4 What does this mean for teaching?

In this section, we discuss whether the differences between the various analyses presented are of any importance for teaching: e.g., do they lead to different teaching

[8] A similar comment applies to Lemke's (1990) thematic analysis. In the "thematic patterns" that he describes, he uses the very words that students and teachers have uttered, and in effect thus also leaves unanswered the question what the relevant themes are.

strategies? The two main strategies that are proposed on both the analysis in terms of misconceptions and the analysis in terms of alternative conceptions are, on the one hand, the use of conflict situations, and on the other, the use of bridging or analogical situations. We will first discuss whether these strategies have application to the case at hand.

The idea behind the use of conflict situations is to confront students with a discrepant event that will more or less force them to abandon, for instance, the ‘static objects are barriers that cannot exert forces’ conception. For us, this strategy is not an option. On our analysis this conception represents the belief that static objects are barriers that cannot of themselves cause something to happen, and there is no reason to make students abandon this belief. This also becomes clear when we try to think of a discrepant event that would cause Jane to dissent from *her* sentence “The track does not exert a force.” Given the meaning that, according to us, she assigns to her expression “to exert a force,” these would be events of the following kinds: the track’s throwing, all by itself, something upward; the track’s giving a slap. Events of those kinds would indeed count as discrepant events, and not just for Jane.

The same sort of comment applies to the other strategy: the use of analogical situations. Clement (1993), for instance, tries to make students overcome the ‘static objects are barriers that cannot exert forces’ conception. He does so by starting from a suitably chosen anchor situation (a hand pushes down a spring). Via some appropriately chosen analogical situations (a book rests on a flexible board; a book rests on a piece of foam), he then tries to make students see that also in the target situation (the paradigmatic book-on-the-table situation), a static object does indeed exert a force. The first thing to note is that Clement’s anchor situation will not be appropriate for Jane if our interpretation of her is correct. When a hand pushes down a spring, she will, as she understands it, answer yes to the question, “Does the person who pushes down the spring exert a force?” but no to the question, “Does the spring exert a force?” Furthermore, in Clement’s analogical situations and target situation, she will answer no to the question, “Does the flexible board/the piece of foam/the table/the book exert a force?” A second note is that she will, of course, agree that the anchor situation and the analogical situations are similar in the sense that in each situation something (the spring, the flexible board, the piece of foam) is deformed, and that the analogical situations and the target situation are similar in the sense that in each situation it is the presence of something (the flexible board, the piece of foam, the table) that prevents the book’s falling down. And she may also come to agree that the various situations are similar in the sense that the table is a bit deformed and, like the spring, the flexible board and the piece of foam, is sort of springy too. Yet, despite all this, she is still right in answering no to the question, “Does the table exert a force?” as she understands it.

We conclude that Clement’s strategy cannot do the job that he has in mind: to make students overcome the ‘static objects are barriers that cannot exert forces’ conception, simply because there is no such thing to overcome. There is no need to make them realise that they no longer hold a belief that they held before. Concerning Jane, for instance, there is no need to make her dissent from *her* sentence, “The track does not exert a force,” and to make her assent to *the teacher’s* sentence, “The track does exert a force." Accordingly, we interpret Clement's finding that students like Jane do indeed assent to the latter sentence as a result of his strategy, not as evidence that they have changed their minds but that they have, at least implicitly, picked up a new use of the expression "to exert a force."

Of course, also Jane could have learned, and explicitly so, her teacher's use of the expression. This may become clear when we think about a way that would have helped them out of their incommensurable discourse: "What the participants in a communication breakdown can do is recognise each other as members of different language-communities and then become translators" (Kuhn, 1970a: p.202). For the teacher and Jane, this would have been a way out. Although they have gone some way in determining in which situations the other holds "This exerts a force on that," they have not recognised that the source of the differences between them is simply due to their attaching a different meaning to the expression "to exert a force on." If they had, they could have become translators instead of convincers. The teacher might then have found that Jane uses the expression as indicated in our section of the source of the argument, and would then have agreed with her utterance of "The track does not exert a force on the glider." He might then also have indicated that he uses the expression in a broader sense, e.g., "*x* exerts a force on *y*" if something happens to *y* (or is prevented from happening) that would not have happened (or would have happened) if *x* had not been there. Jane would then have agreed with the teacher's utterance of "The track does exert a force on the glider," because if the track had not been there the glider would have fallen down. She would then also appreciate that, whereas according to her use of the expression, the similarity between Clement's anchor situation and analogical situations is irrelevant in the sense that she would assent to "The person exerts a force on the spring" but dissent from "The book exerts a force on the flexible board/the piece of foam." The similarity between these situations is precisely the signal for applying the teacher's expression. That is, in each situation there is a deformation of something (the spring, the flexible board, the piece of foam) which would not have occurred if something else (the person, the book) had not been there, and therefore, she would then have agreed with the teacher's utterances of "The person exerts a force on the spring" and "The book exerts a force on the flexible board/the piece of foam." Her then being in agreement with the utterances of the teacher discussed above would not be due to her having changed her mind, or to her having learned something new about the various situations, but simply to her then knowing how the teacher uses the expression. It is only in Clement's target situation that she really might have learned something new, namely, that the table does get a bit deformed when the book is placed on it. Having learned this, it is again just her knowledge of how the teacher uses the expression that would then have put her in agreement with the teacher's utterance of "The book exerts a force on the table."

Let us briefly take stock. We have rejected the aim of making students overcome the 'static objects are barriers that cannot exert forces' conception. We have also indicated that students may implicitly come to use, or explicitly become aware of having to use, the expression "to exert a force on" in a new sense. Let us now state what we do consider to be an important aim, namely, to make students see *why* they should use the expression in this new sense, i.e., *what the point is* of having available a relation that holds between two objects *x* and *y* whenever something happens to *y* (or is prevented from happening) that would not have happened (or would have happened) if *x* had not been there. Moreover, this aim, in our opinion, not only applies to the case just discussed. It concerns, more generally, the introduction of scientific terms in a way that is *meaningful* for students, as part of their entrance into some scientific theory, namely, *to induce* in students *a need*, or at least *good reasons*, for having available the terms that one intends to introduce.

This aim poses a *non-trivial* educational task because, generally, students' reasons or need for having available a particular term cannot, at the stage that it is to be introduced, coincide with what may be called the teacher's or curriculum deviser's reason for introducing it – namely, that having available such a term is useful in the light of a further development toward a scientific theory. In the case of mechanics, we have not yet given this important task enough thought, and therefore we now refrain from making any suggestions. (For similar work on radioactivity, however, see Klaassen (1995).)

We close this section with a discussion, which we admit is rather brief and superficial, of what we consider to be some further consequences of our analysis as regards teaching strategies. Earlier, we have tried to show that there is no need to make Jane abandon her beliefs, because there is nothing wrong with them. Of course, we do not want to make the general claim that students never need to abandon their beliefs. We do claim, however, that in general students do not have to subtract much from what they already believe (that there is no need for extensive changes of mind), but mainly will have to build on and extend what they already believe. In particular, the subtractions will rarely concern claims about what is the case in situations that students are familiar with, because especially such claims must be so interpreted that they are correct. We rather think that most subtractions concern students' expectations of what will happen in a situation that they have never witnessed or paid attention to, namely, when they themselves recognise that what they expected was going to happen does not in fact happen. In such cases students may come to realise that their expectation was implicitly based on some generalisation, and that this generalisation is indeed valid in most situations they have come across, but not in this new situation. The following example may illustrate this.

In everyday life, a thermometer functions as a sort of extension of our senses, which is used to obtain a more precise indication than our senses allow (taking someone's temperature) or to communicate to others how warm it will feel (a weather forecast). What makes a thermometer a trustworthy instrument for these purposes is that it displays a higher number when it, or something, feels warmer. The relations "feels warmer than" and "has a higher temperature than" (i.e., "a thermometer displays a higher number") clearly have different meanings, in the sense that to establish whether the latter relation holds, one has to use a thermometer, whilst to establish whether the former holds, one's own senses. For daily-life purposes, however, they are interchangeable, in the sense that if one relation holds, the other is supposed to hold. Given the mentioned function and use of a thermometer, we would expect that students will expect, before they measure the temperatures of a table's wooden top and one of its iron legs (something they have never done before), that the temperature of the wooden top will be higher. When they then find that the temperatures are in fact equal (perhaps after a recheck with another thermometer), they themselves will of course admit that their expectation has not come true. In this sense, one may say that the experiment poses a conflict. But apart from their expectation, students will not have to withdraw very much. It is still the case that in the situations they had come across before, the thermometer displayed a higher number when it, or something, felt warmer. What they now come to add to this is that there are also situations in which this is not so. So the main point of the experiment is not that students have to abandon something that they held before. Whether there is any use of the experiment in an educational setting depends, of course, on whether it is possible to so embed it in a series of activities that it can be given a further point. It is perhaps possible to precede the experiment by such activities that the experiment provides students with a clear reason to differentiate between the relations "feels warmer than" and "has a higher temperature than," and that the element of surprise that the experiment induces is very likely to prompt their formation of a particular intention, e.g., to find out why in some situations both relations hold, but in others not (what the similarities and dissimilarities are between the various situations). A still further point then might be, from the teacher's or curriculum deviser's point of view, that it prepares a later treatment of heat flow.

We thus arrive at a rough picture of science learning in which students, in a process that involves changes of intention and meaning, come to add to their conceptual resources, beliefs, and experiential base, with the eventual aim of further characterising and explaining more aspects of the natural world.

5 Justification of our analysis: The problem of interpretation and the principle of charity

In our own analysis, and in particular, in the method we have applied to find out what Jane means by her expression "to exert a force," we have, without mentioning the fact, drawn heavily on the philosophy of Davidson (1980, 1984, 1990; see also Stoecker (1993), for an extensive bibliography). In this section, we explicitly pay tribute by showing the relation between our analysis and his philosophy, and by using his arguments to justify the method used. Thus, we implicitly also argue why we think a teaching strategy along the lines sketched in the previous section offers the best opportunities for insightful learning.

Let us begin by briefly summarising our analysis of the quarrel between the teacher and Jane. We have argued that it is not due to a difference of *belief,* to a difference of opinion about *how things are* in *the world.* Instead, we have argued that they have a quarrel because they are not aware that they do not assign the same *meaning* to the expression "to exert a force".

To find out how Jane uses her expression, we have essentially applied the following method. First, detect under which circumstances she selectively holds true her sentences; then, match her expressions to expressions of our own, so that her holding true her sentences and our holding true our matching sentences are systematically caused by the same features of the world. The method may be briefly summarised as follows: assign such meanings to a speaker's expressions that she comes out as consistent and a believer of truths.

Before justifying this method, we now first make contact with Davidson's work. In our analysis we have implicitly pointed to the role that both the concept of belief and the concept of meaning play in an interpretation of verbal behaviour. Davidson noted in this respect that beliefs and meanings *conspire* to account for utterances: we can know what someone believes if we know what sentences she holds true and what she means by those sentences. But after having pointed at this *interdependence of belief and meaning,* Davidson subsequently noted that it gives rise to a problem, which may be called the problem of interpreting verbal behaviour: if we merely know that someone holds a certain sentence to be true, we know neither what meaning she assigns to the sentence nor what belief her holding it true represents.

Davidson also proposed the same method to solve the problem of interpreting verbal behaviour. He developed his argument mainly by considering the situation in which the problem comes most clearly to the fore: interpretation from scratch, i.e., a situation in which two people who speak unrelated languages, and are ignorant of each other's languages, are left alone to learn to communicate. In such a situation we would indeed naturally apply the method above.

What justifies the method is the realisation that our competence to understand one another's verbal behaviour does not *in principle* consist in knowing one another's language. In particular, for communication and mutual understanding to be successful, we do not have to assume identity of meaning. The discourse between the teacher and Jane even shows that the assumption of identity of meaning may lead to severe communicative failures and misunderstandings. In this respect Davidson pointed out that in our everyday conversations there are many occasions in which we cannot rely on the assumption of identity of meaning, and yet manage to understand one another. We might, for instance, think of our ability to perceive a well-formed sentence when the actual utterance was incomplete or grammatically garbled, to interpret words we have never heard before, or to correct slips of the tongue.

What justifies the method is that it enables us to solve the problem of verbal interpretation without having to rely on the notion of an already (beforehand) shared language. As such, it brings out essential aspects both of our competence to understand each other's verbal behaviour and of the common concepts of belief and meaning as we use them to account for each other's verbal behaviour.

Some of the aspects that it brings out are that our competence is essentially a social trait and that the concepts of belief and meaning are essentially of a social nature. It is clear that the method only works in a society of thoughtful creatures that share a natural world. Or, as Davidson put it: "The smallest unit in which the problem of interpreting verbal behaviour can be solved is a *triangle,* two vertices of which are *thoughtful creatures* that are aware (and are aware that the other is aware, and so on) of the triangle, and the third vertex of which is the creatures' *shared* *world of objects and events,* whose properties and existence are independent of the creatures' thoughts."

Another aspect that the method brings out is that our basic competence is governed by a principle that we cannot do without, and that it is only against the background of this principle that the concepts of belief and meaning have application. The principle that necessarily enters in solving the problem of interpreting each other's verbal behaviour is the following, which Davidson called the *principle of correspondence*: assign such meanings to the other's expressions that the other comes out as consistent and a believer of truths (by your own lights).[9]

Our competence can now be characterised as a species of the art of theory (re)construction: what we (re)construct are the meanings we assign to a speaker's expressions, and to make the speaker make sense, our process of (re)construction cannot be but governed by the principle of correspondence.

Let us close by pointing to some of the limitations of this account and the way that they can be overcome by a further extension of the account. The principle of correspondence uses as a starting point the sentences that a speaker holds true. It is clear, however, that nothing can count as a reason for supposing a speaker holds a sentence true that does not assume a lot about her *intentions, purposes, or values.* Indeed, when interpreting Jane, we have tacitly assumed that she did not just want to be stubborn or recalcitrant and that in fact she really intended to make clear why she could not understand the teacher. Otherwise we would not have gone to such lengths in trying to understand her. Another way to highlight this limitation is to note that to solve the problem of interpreting verbal behaviour it is necessary not only to take cognitive attitudes such as belief into account, but also to include *evaluative* attitudes such as desire from the very start, so that the origins of action and intention, namely, both belief and desire, are related to meaning. Davidson in fact argued that the problem of interpreting verbal behaviour cannot be separated from the more general problem of interpreting all behaviour, both verbal and otherwise, which may be called *the* problem of interpretation.

Furthermore, the principle of correspondence can only be applied directly to the most basic cases: utterances that are geared to easily detected goings-on, that are accompanied by pointing fingers, and so on. The principle does not enable two people to interpret each other's more *theoretical* concepts and statements. To interpret those, they will depend much on inferential relations, both deductive and inductive, between beliefs. They must assume that the other, like oneself, gives most credence to the hypothesis most highly supported by all available relevant evidence. Another way to bring out this limitation is that beliefs, desires, intentions, and so on, are not identified only by their causal relations to events and objects in the world, but also by their relations to one another. It is not only the principle of correspondence, therefore, that necessarily enters into solving the problem of interpretation, but also another principle, which Davidson called the *principle of coherence*: assign beliefs,

[9] This addition is not meant as a way of relativising to a particular agent, community, society, paradigm, or whatever. It is rather meant as a reminder of the interpersonal nature of the concepts of belief and meaning.

desires, intentions, and so on, to the other that cohere in the right way.

Davidson's claim is that the general problem of interpretation can indeed be solved by a combined application of the principles of correspondence and coherence. We refer to Davidson (1990) for a substantiation of this claim, which of course depends on a further specification of, in particular, the "in the right way" clause in the above formulation of the principle of coherence. Here we limit ourselves to giving a crude formulation of the *principle of charity*, as Davidson called the combination of the principles of correspondence and coherence: to make someone make sense, we cannot but interpret her (and adjust our interpretation of her) such that she comes out as largely coherent, a believer of truths, and a lover of the good (all by our own lights).[10]

The basic conclusion is and remains, finally, that all interpretation depends on our ability to find *common ground.* Finding the common ground is not subsequent to understanding, but a condition of it. Everything rests on sharing, and knowing that one shares, a world, many reactions to its major features, and a way of thinking with someone else.

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[10] The principle of charity of course also necessarily enters the interpretation of pupils' speech and actions. In a subsequent article, we intend to discuss in somewhat more detail the implications that an awareness of the sources of the problem of interpretation, and the role that the principle of charity necessarily plays in solving it, should, according to us, have for (research on) science education.

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8

Didactics of science: The forgotten dimension in science education research?[1]

> In loving memory of my dearest wife, Yvonne, and my dear friend, Rosalind. Two strong women who died of the same disease.
>
> "I would be quite happy if more research would deal with how to teach X's." (Rosalind Driver, 1994)

Introduction

In this chapter I want to deal with some of the questions that Rosalind and I so often discussed. Questions like "What is actually the value of the research we're doing?" and "How, and in what direction, to go on?" Of course, to answer such questions is not easy and my attempts cannot be anything other than personal constructions! The perspective from which I approach the topic will be that of a (in translated Dutch) 'didactician of physics', that is, someone who deals with the improvement of physics education in all its aspects: through research, curriculum development and teacher training. So, my interest in the field of physics education research is of a rather practical and pragmatic nature. I am not interested in research on understanding teaching and learning as an aim in itself, not even if the teaching and learning concerns physics. What I am interested in, is research which can, and does, improve the practice of teaching and learning physics.

It is often said that science education research suffers from a theory-practice gap (e.g., de Jong *et al.*, 1999). Concerns are expressed about the fact that teachers are too unaware of research outcomes, or about their being unable or unwilling to put those outcomes into practice adequately. This may be true to a large extent, but below I would like to defend the position that, above all, the theory-practice gap is largely due to the nature of the research that is being done.

I also cannot help looking at science education research from the perspective of a physicist. In spite of all the conceptual relativism that is so fashionable nowadays, I still look on physics as a body of largely reliable knowledge with which one can successfully explain and predict, as well as develop new technology. Above all it is

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[1] This chapter is a slightly revised and somewhat extended version of the original publication in R. Millar, J. Leach & J. Osborne (Eds.), *Improving science education – The contribution of research*, 2000, pp.308-326).

a field in which we now know considerably more than, say, thirty years ago. A field of study, that is, in which real progress seems to be possible. Is this also the case for research in (physics) education?[2] I still remember my disappointment when in 1974, as a newly appointed didactician, I had to develop an innovative series of lessons to introduce quantum mechanics at secondary school. I turned to theories of education and educational psychology for help. However, hardly any such help appeared to be available. A frustrating result which, unfortunately, was (and is) in line with the 'natural' scepticism of physicists concerning the 'soft' sciences. That this was not just a personal experience of mine, may be illustrated by the following report by one of the participants at the 1982 AERA Conference. Seven prominent educationalists were given the task of designing a lesson on elementary optics. It turned out, to their increasing amazement, that in spite of their totally different theoretical starting points, the designs turned out to be remarkably similar (de Klerk, 1982). At that time, apparently, educational theories had little specific guidance to offer for the design of educational practice.

Has any progress been made since then, at least for science education? My position regarding this question is, for reasons to be explained below, rather sceptical. Even though, from the past twenty-five years of curriculum development and research, particularly in the field of 'alternative frameworks' as co-initiated by Rosalind Driver, it has become very clear to me that for progress to be made, appropriate science education research is badly needed. But then, what is appropriate?

1 Didactics of science and science education research

In the introduction I have used the term 'didactics of science' as well as the term 'research in science education'. It may be appropriate to go into some more detail as to what might be the differences between the two. Let me first say a bit more about contemporary research in science education. To define it operationally, we have available, among many others, two major recent publications: the *Handbook of Research on Science Teaching and Learning* (Gabel, 1994) and the *International Handbook of Science Education* (Fraser & Tobin, 1998). On the whole, those handbooks make interesting reading (for a researcher, not for a teacher), and give a good impression of, and valuable insights into, many aspects and developments that science education has to deal with. Having said this, however, I also felt rather disappointed after having read through them, because of the *one-sidedness* and lack of *didactical relevancy* of most of the studies reported.[3]

A first feature that is very striking is the almost complete lack of attention to 'science content' (Fensham, 2000). As far as theorising is concerned, science educa-

[2] Although my experience is limited to physics and physics education, from now on I will use the terms science and science education. It is up to the reader to decide whether this generalisation is always justified.

[3] This one-sidedness may well have to do with the fact that both handbooks are primarily USA and/or Anglo-Saxon in nature. In this respect it is worth noting that the term 'didactics of a subject' is quite common in most European languages, but is not used in this sense in the English language.

tion research seems to aim primarily at a content-independent meta-position that closely links with general research in education.

A second feature is the almost complete lack of studies that deal with what I would like to call the 'hard core' of didactics: the interrelation of teaching and learning activities.[4] Little attention is being paid to a thorough didactical conceptual analysis of the content to be taught – a conceptual analysis, that is, from the perspective of learnability and teachability. What is also nearly always lacking is a description and discussion of the didactical quality of the teaching/learning situations that were studied.[5]

What seems to be apparent from the literature is that science education research does not aim at developing content-specific didactical knowledge, possibly to be described as small-scale theories, but at contributing to (if only by simply applying) general educational and/or psychological theories. I consider this 'flight away from content' detrimental, because a level is thereby skipped that I consider necessary for making a real impact on science education and for achieving *didactical progress*. The level, namely, of describing and understanding what is, or should be, going on in science classrooms in terms of content-specific teaching-learning processes, and of trying to interpret them in terms of didactical theory.

This criticism also applies to studies that seek to 'understand' learning processes in great detail. For example, I fail to see the didactical relevance of describing learning processes in terms of detailed cognitive processes (Roth, 1998; Welzel, 1997), or as individual conceptual learning pathways (Scott, 1992). From a didactical perspective, research of the first kind often amounts to little more than describing didactical common sense in complicated cognitive terms, while research of the latter kind is often not interpreted in direct relation to the teaching process (and therefore of little didactical interest).

I also have my doubts concerning the didactical value of conceptual change theory, and theories concerning 'general' problem solving strategies (see, e.g., Hewson & Lemberger, 2000) and/or other 'general' meta-cognitive skills. Quite often such 'detours into the brain' appear to be didactically unnecessary or non-productive. If one attempts to interpret what is going on in science classrooms directly in terms of such general (learning) theories, one immediately faces the problem that on application, such theories, at best, result only in heuristic rules. Such rules simply cannot guarantee that the teaching situations that are supposed to be governed by them will have the necessary *didactical quality*.

How does this relate to 'didactics of science'? In line with my pragmatic and

[4] In fact, in both handbooks, 'teaching' and 'learning' are dealt with in separate chapters.
[5] The following example may illustrate what I mean by this. Recently I had to review a thesis that described the development and evaluation of courseware for an inquiry-based science curriculum. The courseware was said to have 'theoretical quality' as it used a constructivist and inquiry-based view on learning, it was said to have 'empirical quality' as the courseware appeared to have a significant learning effect, and it was said to have 'practical quality' as the teachers appeared to be able to use the courseware in the intended way. However, in my opinion, the courseware showed an important lack of 'didactical quality', i.e., the quality of the designed teaching-learning activities was rather poor.

practical perspective, the aims of 'didactics of science' can be simply formulated as dealing with the basic questions of why, what and how to teach science to whom, in all its aspects. The hard core of this activity, therefore, is not the understanding of (science) learning as a psychological process (though appropriate knowledge about this may, of course, be useful), but the improvement of science teaching and learning. And for this purpose it cannot but focus on the teaching and learning of the contents and other particularities of science as a (school) subject.

Now, of course, every experienced science teacher has much practice-built and/or theory-inspired knowledge about his subject, and about why and how what to teach (of it) and learn (from it).[6] In fact, because of this, in many policy documents and in most educational research that deals with science education, teachers are considered to be *the* didactical experts, who have to transform new curriculum ideas or learning theories into manageable practice. However, past research on 'alternative frameworks', as well as the disappointing effects of the major curriculum development projects of the past, have precisely shown this didactical expertise, even of experienced teachers, to be insufficient. This is not at all meant to disqualify the didactical knowledge of experienced teachers, but only to argue that an extension of such knowledge is badly needed. This cannot be left as a task for only practitioners themselves, but should be considered as an area in need of proper research: didactics of science.

In didactical research two interrelated parts may be distinguished, namely, the problem of curriculum choice and justification (the 'why' and 'what' to 'whom': Fensham, 2000; Millar & Osborne, 1999) in recursive relation to the problem of teaching and learning the chosen curriculum (the 'how'). Research in science didactics thus basically comes down to analysing, describing and improving the teachability and learnability of science. It does not take the science content for granted, but studies it from this particular point of view. Its relation to science itself, therefore, can best be compared with the position of history or philosophy of science.

As far as the content and justification of science curricula are concerned, one cannot, I think, properly speak of scientific progress. As the mathematics educator Freudenthal (1991) once remarked: "Pictures of education taken at different moments in history are incomparable. Each society at a given period got the education it wanted, it needed, it could afford, it deserved and it was able to provide. Innovation cannot effect any more than adapting education to a changing society or at best can try to anticipate on the change. This alone is difficult enough."

In my opinion, things stand differently with regards the 'how'. Although I completely disagree with Fensham (2000) that "there is now no shortage of pedagogical knowledge in science education", I do think that progress in science didactics with respect to such knowledge is possible, provided we intensify our search for it. Such a search asks, I think, for a special methodology, namely, 'developmental research' (Lijnse, 1995; Gravemeijer, 1994), which is rather similar to what others have called 'design experiments' or 'teaching experiments' (Erickson, 2000). Though

[6] This often non-reflective level of knowledge of didactics of science comes probably close to what is nowadays called 'pedagogical content knowledge' in the English literature.

such research should take the didactical knowledge of experienced teachers quite seriously, its task is to seek essential improvement and scientific extension of it. This can probably best be done by developing exemplary practices as regards the teaching of specific topics. Starting from explicit views of science and science teaching and learning, such developmental research involves a cyclical process of conceptual analysis, small-scale curriculum development with teacher co-operation and training, and classroom research on teaching-learning processes. In this process, one should of course apply anything that is useful (one's scientific knowledge, psychological theories, views from history or philosophy of science, and so on).

Through reflection on such practices, one might come to formulate content-specific theories regarding the teaching/learning of particular topics, which can perhaps be generalised to a certain extent to similar topics. And maybe one may even come to formulate more general 'theoretical' principles for 'good' science teaching and learning. Thus one could give content to didactics of science as a scientific activity.

In the above I hope to have made clear that science didactics differs considerably from mainstream science education research. The main distinction (as I see it) is this:

- The primary aim of (research in) science didactics concerns content-specific didactical knowledge, based on developing and justifying exemplary science teaching practices;
- Mainstream (Anglo-American) science education research seems to be primarily aimed at a description and theoretical understanding of (existing) science teaching practices, mainly in terms of content-independent factors.[7]

Although there may be overlap between the two, I think this difference in focus is a major reason for the problematic practical relevance of science education research. Didactics, taken as a scientific activity, can, I think, best be characterised as a form of *educational engineering*, while much of science education research seems to aim at understanding teaching and learning (science) as a *theoretical science*.

Perhaps I should add that I am not at all against trying to develop or apply general theories. On the contrary, I think that in scientific work we always have to go back and forth between the specific and the general to make progress in our theories. My problem is, however, that in dominant science education research, the general focus is taken from the start as being in the psychology of the brain, or in the sociology of the classroom, or in the philosophy of science, and so on. And thus neglecting a necessary intermediate didactical level, with its content-specific aspects.

Take, for example, the intensive discussion about constructivism(s), which comprises a large number of philosophically tainted papers. As summarised and

[7] For example, in an Editorial of a recent issue of IJSE, Roth writes: "An increasing number of studies in recent years were designed to generate better understandings of learning processes. [...] The learning process studies [*in this issue, P.L.L.*] describe in detail interrelations between various aspects of the instructional setting (social configuration, artefacts, materials, discursive resources) and cognitive processes during teaching-learning situations."

interpreted (rather charitably) by Ogborn (1997: p.131), the possible didactical relevance of this whole discussion is rather limited and boils down to four simple ideas:

- 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 on and using what they know and addressing difficulties that may arise from how they imagine things to be.

It is hard to think of anyone who would not agree with those ideas.[8] So the real issue does not concern the theoretical or philosophical validity of those four starting points of what I would like to call *educational constructivism*, but rather the *didactical quality* with which they are applied in practice. Heuristic guidelines do not suffice for that. However, this problem has, as yet, hardly been taken up as a task for researchers in science education. Its solution is largely left (as an impossible task) to teachers.

Apart from this discussion about constructivism, the stage of science education research has been dominated by topics like mental models and modelling, problem solving and other general cognitive and meta-cognitive processes and strategies, cooperative learning and co-construction of knowledge in communities of learners, apprenticeship and scaffolding, metaphors and analogies, language and semiotics. Partly inspired by all of this and partly for other reasons, there has also been a spectacular rise in attention paid to the history and philosophy of science, in short, to the 'nature of science'. Noticing all those developments, Duschl and Hamilton (1992: p.7) wrote: "We find ourselves, then, at a critical and exciting time in science education." It may be clear from the above that I am less excited. All the developments mentioned seem to take place predominantly within a circuit of theorising (science) educators, staying relatively far away from the didactical practice of the science classroom, and resulting at best in 'implications' for (science) teaching. And therefore hardly leading to didactical progress.

2 A case study: Teaching about the particulate nature of matter

In order to further clarify my points of discussion, I will compare two approaches to teaching an introductory particle model. The first approach is taken from the CLIS Project (1987), which developed a number of influential teaching materials that (though probably unintended by its authors) are often referred to as paradigms of constructivist teaching strategies. The second approach is developed as part of a PhD research study (Vollebregt, 1998).

In view of some of my criticisms above, my choice of the CLISP work may

[8] Some people might argue that a fifth point should be added, viz., that pupils' ideas have been shown to be strongly resistant to change. However, as yet, it has only been shown that such ideas are strongly resistant to our teaching, underlining the necessity of didactical progress.

seem strange at first instance. For the CLIS Project did not stop short by just formulating some general implications, but also made quite an effort to put these into practice. Nevertheless, I consider it as an example of mainstream science education research in that its focus was on applying 'the constructivist view of learning'. As a result the CLISP approach suffers from severe didactical shortcomings. Or at least so I will argue, by contrasting it with our own approach.[9]

The CLISP approach

The CLISP view on learning involves the idea that "pupils come to science lessons already holding their *own* ideas about natural phenomena which they have developed through everyday experiences: pupils are not empty-headed" (CLISP, 1987). In line with this, a number of pupils' ideas about matter *prior* to formal teaching, as found in previous research, are described. While taking account of those ideas, a teaching scheme is then worked out that has the following aims:

- To introduce pupils to the particulate theory of matter as a theory that is useful in explaining a large number of seemingly unconnected phenomena relating to the nature and behaviour of matter;
- To introduce pupils to scientific theory making as an activity which they can validly engage in.

The teaching scheme itself is based on a generalised teaching sequence proposed by Driver and Oldham (1986), which consists of the following phases:

> *An elicitation phase*: Where students are provided with opportunities to put forward their own ideas and to consider the ideas of their peers.
> *A restructuring phase*: Where the teacher introduces activities which interact with students' prior ideas and which encourage students to move their thinking towards the school view.
> *A review phase:* Where students are asked to reflect on the ways in which their ideas have changed.

The application of this general scheme to the topic of particle models is described in some detail by Johnston (1990). The approach begins by asking pupils for their own ideas about a number of simple phenomena relating to the behaviour of matter (e.g., how smell reaches you). By means of a number of theory-making games that are set in non-scientific contexts (e.g., solving a murder mystery), pupils are then encouraged to reflect on their understanding of theories and how those are developed. Next, pupils are asked to put forward their own ideas about the properties of solids, liquids and gases and are stimulated to reach consensus on a pattern of properties. Subsequently, pupils are to generate a theory as to what solids, liquids and gases are like inside, while they are reminded of the general nature of theory making and en-

[9] In this section I use the plural for two reasons. First, the PhD research study in which the approach was developed was partially a group effort, to which not only Marjolein Vollebregt and I contributed, but also Kees Klaassen and Rupert Genseberger. Secondly, this section is my adaptation of a draft paper by Kees Klaassen.

couraged to base their theory making in the case at hand upon the agreed pattern of properties of solids, liquids and gases. Although up to this point pupils are left free in what they bring forward, it turns out, as was expected and/or intended by the devisers:

- That in a wide range of classes pupils reach consensus on a similar sort of pattern of properties (e.g., solids have a definite and fixed shape, liquids take the shape of the container, gases have no shape but rather completely fill the container).
- That pupils generate particle models in order to account for the behaviour of solids, liquids and gases as described by the pattern (e.g., a solid cannot be compressed because its particles are so close together that they cannot be pushed any closer).
- That some of pupils' particle ideas are alternative (e.g., they attribute macroscopic properties such as expanding to particles or hold that there is air between particles).
- That some ideas of the school science view are lacking in pupils' particle models (e.g., particles have intrinsic motion).

The heart of the CLISP approach then consists in making pupils evaluate, develop and change their alternative ideas and adopt the appropriate scientific ones, e.g., by thought experiments to encourage them to consider the possibility that there might be nothing between particles, by diffusion demonstrations to make them recognise that particles have intrinsic motion, or by direct explanations of what scientists think.

Evaluation studies (Johnston, 1990) showed that "most students appeared to enjoy the scheme and appreciated the opportunity to become actively involved in their own learning". In particular, "the most able students appreciated being given the opportunity to think in depth about an area of science." However, a comparison study between two parallel groups, of which one used the CLISP approach and the other the school's traditional approach, showed that "there was little difference [...] overall in the conceptual change produced" (Driver, 1989).

Some comments on the CLISP approach

A first thing to note about the CLISP approach is that 'particle ideas' or 'particle models' are attributed to pupils because they use words like 'atom', 'molecule', or 'particle', and/or draw discrete entities in their pictures of what matter is like inside. Furthermore, some of their particle ideas are counted as alternative because they attribute macroscopic properties such as melting or expanding to particles. This is in line with numerous studies that have been conducted on 'the way pupils relate microscopic particles to macroscopic phenomena' (Lijnse *et al.*, 1990).

Now, one is of course free to call what pupils bring forward 'particle ideas' or 'particle models'. But we think one should then also clearly bear in mind that their ideas are not about the particles that figure in scientific particle models, and that their models are of a different nature from scientific particle models. For we think it is clear from the way pupils use words like 'particle of...' or 'atom of...', that one cannot do better, in order to make them make sense, than interpret them as 'tiny bit of...'.[10] So the statement that pupils come up with ideas about 'particles/atoms', some of which are alternative, then simply amounts to the statement that pupils believe that a substance can be divided in little bits that, apart from their size, are just like larger amounts of the substance (have the same macroscopic properties, are subject to the same macroscopic regularities, and so on). Their particles simply *are* small-scale macroscopic objects, and their particle models essentially *are* macroscopic accounts. So one should be very careful with the conclusion that it is "common for students to attribute macroscopic properties (such as melting or expanding) to particles" (Johnston, 1990).[11] If we read it as 'pupils attribute macroscopic properties to *our* molecules', we will be misinterpreting them: they are *not* talking about our molecules. Concerning our molecules, we think it is best to say that they do not have any ideas at all (Klaassen, 1995).

However, because of its emphasis on the supposedly alternative particle ideas that pupils are to change in favour of appropriate scientific ones, which after all is the heart of the constructivist teaching sequence, the CLISP approach in effect does equate pupils' particles to the particles that figure in scientific particle models. Or, to put it from the pupils' point of view: in the CLISP approach they are to replace some of their existing ideas about *their* particles by other (and quite strange) ideas about *their* particles, which are then called 'scientific'.

So in our opinion the CLISP approach misfires. If appropriately interpreted, there are no alternative beliefs to overcome (e.g., there is no need to make pupils abandon the idea that *their* particles expand when heated) and to be replaced by 'scientific' ones (e.g., there is no need to make pupils learn that *their* particles have intrinsic motion or that there is nothing between *their* particles). Moreover, by unjustly equating pupils' particles to the particles that figure in scientific particle models and by treating their particle models on a par with scientific particle models, the CLISP approach also cannot lead to a proper understanding of scientific particle models. At best, pupils will arrive at a hybrid between their particle models (in essence, macroscopic accounts) and scientific particle models. And thus the negative result of the comparative study cited above comes as no surprise.

Description of a 'problem-posing' approach

Starting points

Let us now describe our approach to the introduction of an initial particle model, in order to be able to point concretely to the sort of didactical considerations we think are lacking from the CLISP approach. In developing our approach, we have taken as a first starting point what above has been called 'educational constructivism'. We do not adhere to the 'alternative framework' movement, however, and therefore did

[10] For a further discussion of the general 'problem of interpretation', and of the interpretation of pupils' utterances in science education in particular, see Klaassen (1995) and Klaassen & Lijnse (1996) (reprinted as chapter 7 in this volume).

[11] A similar conclusion applies more or less to much more reported research results on pupils' alternative frameworks.

not try to develop ‘constructivist teaching strategies’ nor try to apply ‘conceptual change theory’. The reason is, as will have become clear from the above, that we do not think pupils have ‘alternative’ ideas about particles that need to be changed. As far as cognitive learning is concerned, we think it is best to think of science learning as a process in which pupils, by drawing on their existing conceptual resources, experiential base and belief system, come to add to these (with accompanying changes of meaning). What we think needs to be added to this picture, as a second starting point, is that if this process is to make sense to them, pupils must also be made to *want* to add to them. Or, in other words, 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, the process of teaching and learning will make sense to pupils, and it can be expected that they will then accept new knowledge on grounds that they themselves understand. An approach to science education that explicitly aims at this, we call *problem posing*.[12] The emphasis of a problem-posing approach is thus on bringing pupils into such a position that they themselves come to see the *point* of extending their existing conceptual knowledge, experiences and belief system in a certain direction.

Thus formulated, this second starting point seems rather trivial, and indeed it is. Since in themselves the starting points give hardly any didactical guidance, the real non-trivial challenge lies in the didactical quality with which they can be put into practice.

A scientific particle model

Let us first give an indication of what the didactical task of making pupils see the point and direction of a process that eventually leads to a proper understanding of scientific particle models might consist in. In order to achieve this, we think that it should not only become clear to pupils that devising a scientific particle model is a form of theory making that, just like, for example, solving a murder mystery, involves framing tentative hypotheses on the basis of available clues, but foremost also that it is the making of a theory of a *characteristic* kind. Moreover, making it of this characteristic kind imposes constraints on the framing of hypotheses.

What is characteristic about a (classical) scientific particle model is that it aims to understand the behaviour of matter by assuming that matter consists of invariant ultimate components (the particles) whose positions and velocities change due to their mutual interactions. The two basic aspects of any such model are, therefore, ‘invariance’ and ‘motion’, which are related in the sense that if all change ultimately has to be understood in terms of basic components that themselves are invariant, this can only be in terms of the basic components being in motion.[13] All change, that is, then ultimately is motion. In order to arrive at a specific particle model, one will obviously have to supplement these basic aspects with hypotheses

[12] To achieve this, we often try to bring pupils in such a position that they themselves come to pose the main problems that they intend (and have) to work on. This is why we have termed our approach ‘problem posing’.

[13] Note that this clearly distinguishes the basic components from pupils’ particles, i.e., from essentially macroscopic tiny bits.

that allow one to derive, given the initial positions and velocities of the particles, their positions and velocities at a later time, e.g., hypotheses concerning the way the particles collide, or concerning the interactions between the particles.

The only way we can test the model is, in essence, by macroscopic phenomena. So what will have to be added, in order to give the model empirical content, are hypotheses of another kind. Hypotheses, namely, that specify the macroscopic states of an object as functions of the microscopic states of the system of particles, e.g., the connection between the temperature of an object and the mean kinetic energy of its particles.

The brief characterisation above can be said to indicate a general framework within which further specific hypotheses are to be made in order to arrive at a specific scientific particle model. We therefore think that the previously identified didactical task of making pupils see the point and direction of a process that eventually leads to a proper understanding of scientific particle models, consists in making pupils arrive at sufficient insight into this general framework and into why it is as it is. This way of putting the didactical task not only shows that the CLIS project underestimated the necessity of a thorough conceptual analysis of the content to be taught, but also that general accounts of models and modelling, as for example given by Gilbert and Boulter (1996), are of little didactical relevance in this respect.

Solving the didactical problem of how to meaningfully make pupils partners in an enterprise that aims to explain, under the assumption that an object is a certain collection of particles, all changes of that object solely in terms of changes of position and velocity of those particles due to their mutual interactions, is of course far from simple. Among other things, the following should become clear to pupils. Why, in the first place, one would want to improve on one's macroscopic understanding of the behaviour of matter. Why, if there is a need for improvement, it is plausible, in order to attain the desired improvement, to assume that an object is a collection of particles. In what sense those particles differ from small-scale macroscopic objects (tiny bits). Why one wants to give explanations solely in terms of changes of position and velocity of the particles, and why it is plausible to expect that all (or at least a great number of) macroscopic changes can be explained in those terms. Why, in order to give such an explanation, one needs the two kinds of hypotheses mentioned above, and what the explanation then consists in. How further specific hypotheses can be arrived at. In what sense a specific particle model can be called better than another one.

We hope this suffices to not only make clear that the real didactical task is nontrivial, but also that the CLISP approach does not meet it, and, in fact, draws one's attention away from it. What we would like to retain from the CLISP approach is to give pupils an active role in the process. They enjoy that and will thus be more involved.[14] But whereas in the CLISP approach their involvement in effect consists in

[14] In this sense we have built on the CLISP work. We also used as much as possible from a number of French studies on teaching of particle models (Lijnse *et al.*, 1990). This shows that in order to make progress, also at the detailed level of content-specific didactics, it is necessary to build on previous research.

their bringing forward ideas about *their* particles, we would like it to consist in their seeing the point and direction of, and their having control over, constructions and reconstructions of specific *scientific* particle models.

A didactical structure

Lack of space prevents me from describing here in any detail the actual sequence of teaching activities that was designed, trialled and revised several times. So I will make do with describing and discussing the final product (so far) of the research, i.e., a schematic description of a didactical structure for the teaching of an initial particle model in a way in which pupils are actively involved in the process of modelling. The structure relates to an approximately ten-lesson sequence for pupils of age 16 in our schools for upper level secondary education. This reflects the point that outcomes of didactical research such as this are not only content specific but also to some extent system specific, as they apply in the first place to a particular niche in a particular educational system.

Some remarks may shed more light on this structure. The left-hand column consists of knowledge of physics, and the right-hand one of knowledge of the nature of physics. The arrows show how the process of teaching and learning switches between columns and how these switches come forward naturally because of motives that are developed. These motives constitute the middle column. The structure shows that because of the problem-posing character, our two main content-specific aims, i.e. learning to use a particle model insightfully in explaining macroscopic behaviour of matter, and obtaining insight into the nature of particle models and scientific modelling, have been worked at not only in relation to each other, but more strongly, in dependence of each other. Thus, learning at both 'levels' *drive* each other in a natural way.

From the didactical structure above a more general structure may be abstracted, consisting of phases that switch between a content level and a reflective level. We feel that this more general structure provides a possibility of generalisation to the teaching of other topics and skills.

A particular problem has to do with inducing an initial necessary 'theoretical orientation', i.e., to make pupils see the point of looking for a deeper understanding of macroscopic knowledge and to make them prepared to start learning about *scientific* particles. In fact, this standard problem of a first introduction of particle models cannot be solved by inducing more 'macroscopic' questions, as these can always be answered with still more macroscopic knowledge. As this different kind of understanding goes along with a qualitatively different kind of (model-theoretical) reasoning, it does not make sense at this point to ask pupils for *their* ideas about the structure of matter, because this *cannot result in anything else but 'theories of tiny bits'*. The problem is how to induce a preparation for a plausible introduction of an initial quite different model.[15] Normally, adequate analogies are natural tools for making a first step in introducing people to something quite new. For the purpose at

[15] The historical motive of Democritus, which had to do with explaining 'being and becoming', presupposes such a deep level of interest that we cannot assume this to function for our pupils.

hand we think of functional or mechanistic explanations, e.g., of the capacities of an organism in terms of component organisms, or the working of a clock in terms of springs, cogs, and so on. The initial model is then further elaborated, by pupils and teacher together, in a process of making and testing hypotheses.

Physics knowledge	**Motive**	**Nature of physics**
Global orientation on something like 'structure of matter' →		← as a topic of scientific interest and progress
	↓ should result in a feeling that this could be an interesting field of study	
↓ that starts by narrowing the field down to macro knowledge of gases →		on which is reflected in relation to students' tacit knowledge of the aims of physics
	resulting in a willingness to look for deeper understanding (theoretical orientation) ←	
↓ by means of an initial kinetic model, introduced in such a way that it is initially plausible, because it is intelligible and seems fruitful		
↓ involving students in a disciplined modelling process that leads to a further development of the model with increased plausibility →		
	but also to questions about its fruitfulness →	
		↓ that are answered by reflection on the properties and existence of particles and on particle explanations
	from which a suspicion about a fruitful 'research programme' should result ←	
↓ that is explored by a further development of the gas model and its application to the behaviour of liquids and solids as well →		
	leading to a point of closure at which we may ask 'what have we done?' →	
		↓ that is answered by reflection on the process of modelling in relation to 'how scientists work'
	resulting in an outlook on subsequent modelling ←	
↓		

In describing our structure retrospectively, we have used 'status terms' from conceptual change theory (intelligible, plausible, fruitful). This is not because we *applied* this theory in our didactical design, but because they appeared to have been built in, in a natural way.[16]

The didactical structure above describes, given the chosen aims, the essential steps of a conceptual and content-related motivational pathway through the topic, that has been shown to be possible for pupils. In our research, it is abstracted from an empirically tested scenario, in which the didactical choices are motivated, that describes the probable teaching-learning process in great detail, from the perspective of both teacher and pupils. And thus, as formulated above, from the perspective of learnability and teachability.

Comparison

Now what may we conclude from a comparison of both approaches? If we consider the CLISP approach as a paradigmatic example of what the constructivist research paradigm has to offer for didactics, then our conclusion is that, apart from some original teaching activities, it has predominantly to do with making pupils more actively involved in the learning process. So, with an undoubtedly important but general aspect of their teaching strategies. At the content-specific level, their emphasis on constructivism even seems to have led them on a wrong track. Apart from having pupils actively involved, we may conclude from our own work that further theoretical ideas from the contemporary literature are neither necessary nor very helpful at the didactical level.

Instead, a more thorough didactical conceptual analysis, i.e., in terms of what conceptual steps pupils have to make *from their point of view* in order to be able to come to understand the content matter in the intended way, and a real effort to design teaching that succeeds in making these steps acceptable for pupils, seem to be much more important. In this respect, we think that, compared to the CLISP approach and to others (Meheut & Chomat, 1990), we may speak of having made didactical progress.

3 Discussion

Now let us go back to where we started. I have argued that (Anglo-American) science education research is very much focused on explaining science education within a psychological, sociological, linguistic and philosophical context. This has, without any doubt, led to important insights into what is going on in science classrooms. At the same time, however, it is hard to apply such research to science education practice, because it does not pay much attention to the didactical level, i.e., a

[16] This does of course not apply to the term 'dissatisfaction', in line with the fact that we did not start from alternative ideas. Instead of dissatisfaction, we could say that we used the motive of curiosity.

didactical analysis of the content to be taught and the design of teaching-learning situations with sufficient didactical quality. As a consequence, most science education research suffers from a severe theory-practice gap. To illustrate this problem I have described two approaches for the introduction of an initial particle model.

This example also illustrates the necessity of taking didactics of science as a research field in its own right. A possible and necessary (long-term) outcome of such research could be didactical structures for all of science (or for that part that may be chosen to be in the school curriculum). Structures that could play an essential role in making the present negative image of science as being incomprehensible and irrelevant disappear as much as is possible. Starting from a thorough analysis of science and scientific knowledge in terms of underlying basic common-sense intuitions, conceptual and motivational pathways should be developed and didactically tested that describe the essential conceptual steps that have to be taken, how they build on and prepare for each other, and how pupils and teachers may walk them together.

Now, it is often questioned whether, or to what extent, research can deal with how to teach a topic most effectively. As Tiberghien (2000) remarks: "designing teaching situations for each domain of physics and for each level" is an endless task. Therefore in her research she focuses, within the French didactical tradition[17], on the design of teaching situations that are representative of a *set of situations* by making use of more general *characteristics* of physics knowledge. Though we agree that the outcome of didactical research cannot only be at the level of teaching situations themselves[18], we have taken a different route, i.e., we offer the idea of an empirically supported 'didactical structure of a certain topic'. Such structures describe well-motivated possible routes to solutions of didactical problems that are either brought forward by teachers or result from previous research. Of course, such structures, together with their worked out teaching scenarios, cannot succeed without the experience and craftsmanship of good teachers. As such, they are not 'teacher proof'. They also cannot guarantee the successful learning of individual pupils. However, they do provide even experienced teachers with new didactical insights which can improve their teaching considerably at essential points, and they do describe, and predict the feasibility of, an 'average' classroom learning process. Thus they can improve the learning and teaching of a certain topic in the sense that more pupils will understand and value what they have been taught.

If more research dealt with such didactical structures (or whatever one wishes to call them), then, from mutual comparisons and discussions, even more didactical progress would be possible. And even though 'the best way of teaching a topic' may always remain an illusion, improved ways of teaching could result that could

[17] The French research in 'didactique' tries to describe essential didactical aspects of teaching/learning situations. Therefore terms like 'didactical transposition', 'didactical contract', 'devolution', and so on, have been framed.

[18] Though it is essential that the research is based on the development of exemplary situations. These serve to empirically test didactical hypotheses, thus forming the basis for theoretical reflection, and at the same time they serve as concrete and tried out operationalisations of these reflections, thus preventing a theory-practice gap.

be considered as (more) satisfactory. And that would be a significant result, indeed!

In my opinion, research in science didactics thus has the task of filling an essential gap between science teaching practice and Anglo-American research in science education. The adjective Anglo-American is meant to indicate a restriction in this context, as in many continental European countries (research in) science didactics seems to have a much more developed role. This has probably to do with the fact that in many European countries didactics has a long tradition, even though this tradition may differ from country to country. A recent review of European PhD work in science education concluded that much research is being done on the teaching and learning of X's, in which X stands for a particular science topic (Lijnse, 1994) – a conclusion with which Rosalind Driver could well approve. In 1988 she wrote: "An important point to make here is that the curriculum is not something that can be planned in an 'a priori' way but is necessarily the subject of empirical enquiry."

In view of this, the essential role that she played in establishing a European Science Education Research Association (ESERA) should also be mentioned here. It would be an important achievement for science education if ESERA could succeed in crossing the language and cultural borders within Europe (and elsewhere) and give research in didactics of science a more prominent role on the science education research agenda.

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9

Methodological aspects of design research in physics education[1]

Introduction

Recently, a special issue of the *International Journal of Science Education* was devoted to research on designing teaching-learning sequences, and two special issues of other journals were devoted to the methodology and aims of design research.[2,3] In Europe, design research already has a considerable history, albeit under different names and in different varieties, such as developmental research, ingénierie didactique or educational reconstruction (Meheut & Psillos, 2004). In a review presented at the second ESERA PhD Summer School, I concluded that many research projects had to do with designing strategies for teaching X's (Lijnse, 1994), where X stands for some scientific topic or concept. In Utrecht, our work on design research grew out of our experience with curriculum development (PLON) and on early research in physics education (Lijnse, 1985). Now, what is design research in physics education? Its main characteristic is that it does not deal with investigating *existing* teaching situations, but with developing and testing *new* teaching situations. The literature shows several approaches, but in its content-specific didactical format, design research deals essentially with questions like 'how to teach X', or 'how to teach X better'. It does so, necessarily, from a particular didactical perspective (e.g., a problem-posing approach) that acts as a guiding theoretical framework[4,5,6]. So, it is not

[1] This chapter is a slightly revised version of the paper 'Developmental research: its aims, methods and outcomes', originally published in M. Michelini & S. Pugliese Jona (Eds.), *Physics teaching and learning*, 2003, pp.55-66. Copyright 2003, Forum. Reprinted with permission of Forum.

[2] In previous publications I have used the term 'developmental research'. In a number of recent American publications, however, the term 'design research' is introduced, to which I shall adapt myself to avoid unnecessary diversity in language.

[3] This concerns issues of the *International Journal of Science Education 26*(5), 2004, *Educational Researcher 32*(1), 2003, and the *Journal of the Learning Sciences 13*(1), 2004.

[4] With the European term 'didactical' I mean that the study of the interrelation of teaching and learning activities and processes concerning the subject matter involved, is the core of our work.

[5] Let me give some examples. At Utrecht University, recently, the following PhD theses were defended: *A problem-posing approach to teaching the topic of radioactivity*, *A problem-posing approach to teaching an initial particle model*, and *A problem-posing approach to teaching decision making about the waste issue*.

[6] To avoid misunderstanding: this 'problem-posing approach' is just one example of such a didactical perspective. It is not connected to the idea of design research as such. One may develop a problem-posing approach to a certain topic, without going into a process of design research. Just as one might operationalise any other didactical perspective by means of design research.

concerned with investigating the working of the mind, the sociology of the classroom, the semiotics of teaching materials, or the intuitive conceptions of teachers and pupils, though such research may, of course, sometimes result in useful implications for teaching X's.[7] Instead, it tries to create new content-related didactical knowledge by investigating the teaching-learning *process* within *exemplary teaching practices*. Didactical knowledge that, as a consequence, will then be empirically supported and theoretically justified. "Design research is not done following a strictly regulated methodology but, rather, as a way of working that grows through being put into practice. Only by reflecting on such practice can it take shape as a method." (Gravemeijer, 1994). In the following I will describe some of the main aspects of this way of working, that are, in my opinion, relevant for anybody who is dealing with developing and testing actual teaching activities in the context of his or her research, whether or not he or she uses my terminology.

1 Why design research?

Research in physics education is still a relatively new field of work. As a consequence, there is not one accepted research paradigm. And probably there never will be, as research approaches from different perspectives have different contributions to make. However, the relation between the outcomes of our research and educational practice has been a matter of much concern (de Jong *et al*., 1998). What kind of research can be really useful for the improvement of practice (assuming that we accept this as a main goal of our research, which not everybody does)?

In the distant past, we had separate fields of expertise with clear relations. *Practitioners* had to do the actual teaching using wonderful newly developed textbooks. Those were written by professional *curriculum developers* who developed innovative curricula. The curriculum developers, in their turn, were inspired by *educational researchers* who tried to understand and explain learning and teaching, formulating learning theories with implications for teaching and theories of curriculum innovation. However, we all know that the success of this so-called RDD-strategy has been very limited.

Nevertheless, we still recognise this kind of 'implications for practice' strategy in much present-day work that, in the first place, tries to understand and explain physics education in terms of more general ideas, taken from theories as constructivism(s), information processing, semiotics, cognitive science, and so on.

From a didactical point of view, however, I would say that such an implications-for-practice strategy is too much top-down, or, in short, too much theory and too little action. It does not recognise the level of didactics as an essential topic of re-

[7] These research approaches aim to describe science teaching situations in characteristic categories that are derived from the application of general theories. They are thus in the first place aimed at *understanding* science teaching in terms of the chosen theoretical perspective. Such an understanding might then subsequently be used to improve the practice of science education. In my opinion, the latter often appears to be very difficult (Lijnse, 2000).

search in its own right (Figure 1). That level, the interaction of teaching and learning activities and actions in the classroom, is too often skipped over or left to the teacher.

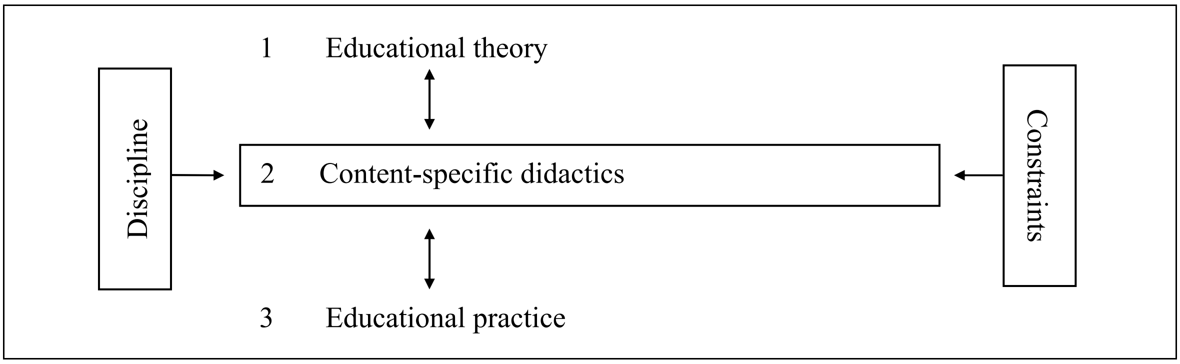

Figure 1 – A simplified view of the level of didactics, between general educational theories and educational practice, and taking into account the disciplinary knowledge and skills that have to be taught, as well as the institutional constraints of the teaching situations.[8]

In other words, in much research too little attention is paid to the didactical quality of the teaching situation. In my view, design research aims to fill this gap, as it focuses precisely on the level of didactics. It is not primarily aimed at explaining and understanding, but at enabling *action* and *change* (Freudenthal, 1991). In our work at Utrecht, therefore, small-scale curriculum development is combined with test development, teacher training and classroom research on teaching-learning processes, in a cooperative effort of researchers and teachers, taking place in a cyclical process of gradual improvement. Thus, it is the dissatisfaction with the shortcomings of traditional curriculum development on the one hand, as well as with those of the implications-for-practice type of research on the other, that forms a major rationale for design research.

As already indicated, this type of research is becoming more popular nowadays, as it is felt more broadly that the usual gap between 'theory-driven' research and practice needs to be bridged. As the educationalist Van den Akker (1999) writes: "A basic motive stems from the experience that 'traditional' research approaches (e.g. experiments, surveys, correlational analyses), with their focus on descriptive knowledge, hardly provide prescriptions with useful solutions for a variety of design and development problems in education." Therefore, what he calls, 'design studies' or 'development research' have become more fashionable. However, even such studies may differ from the work I am talking about as, again, they may not be aiming at the didactical level, but at more general outcomes as may be clear from the following comment (van den Akker, 1999): "…the professional community of developers as a whole would be helped by a growing body of knowledge of theoretically underpinned and empirically tested design principles and methods."[9]

[8] Of course, one might always ask whether the arrows that have been drawn are the right ones, and whether not much more should be drawn.

[9] This extract reflects a major point of criticism against design research. In fact, many general educationalists are tempted to say that such didactical research is not proper research at all, but only a

2 Methodological aspects

Role of the researcher

In design research, the role of the researcher is rather different from that which is common in traditional educational research. In the latter, the researcher is primarily an objective observer and interpreter of what is going on in classrooms, but in the former he is an active participant in the design of a new didactics. He is not just studying what is going on from outside, but is first shaping his object from inside. In fact, he performs a teaching experiment, in which he is responsible for the didactical design, the teacher training, the tests, and so on. In other words, he is testing out and developing his own hypothetical didactical knowledge. As a consequence, a major outcome of such research is the *didactical learning process of the researcher*.

This results of course in specific methodological problems because, when I am talking about the learning process of the researcher, I have to make a distinction between the learning process that is necessary to *reach* the frontiers of our didactical knowledge, and the process that *extends* these frontiers. It is of course only the latter that can be considered a real research outcome. However, this asks a lot of a design researcher. He should be knowledgeable about the usual didactical approaches regarding his topic, be knowledgeable about the relevant research literature and theoretical ideas that he wants to apply, be able to develop and justify a new didactical approach, and above all, be able to design a teaching sequence in such a way that teachers are able and willing to put his ideas into practice *as intended*. All together, this requires very diverse competencies, and the danger is very great that the research does not test the frontiers of our public didactical knowledge, but only the frontiers of the competence of the researcher.[10]

In our work at Utrecht, we try to deal with these problems by working in teams, in which experienced teachers play an essential role. By setting up a close cooperation with one or more teachers, the craft knowledge that experienced teachers have developed plays its necessary role in the design and trying out of new teaching sequences.

Explicit viewpoints and critical details

Education is a value-laden activity, and in order to be able to judge new didactical solutions properly, they should be placed within and justified from their underlying theoretical perspectives. So the design of a teaching-learning sequence, as a central element of a design research cycle, should be guided by formulating *explicit views*

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detailed way of developing teaching materials. In my opinion they then not only underestimate the importance of content-specific didactical knowledge as a research outcome, but also overestimate the importance of general principles and methods. In fact, both are needed, preferably in direct relation to one another.

[10] This problem is perhaps not restricted to this type of research. It could be a reason why so little PhD research is published internationally, as many studies seem not only to focus on local problems, but also to result in knowledge that is only locally new.

on teaching and learning, as well as on science and science education, integrated into what could be called a concrete topic-related *view of good science education*.[11] In fact, in most design research, this underlying view is not really opened up for discussion. It may, in fact, be regarded as the hard core of the research programme, which is of particular importance when we consider design research from a curriculum-change perspective.[12] In design research, it is the didactical operationalisation and optimalisation of the principled choices made that are at stake.

For instance, one might choose to adopt a social constructivist view on learning or to strive for scientific literacy. Choices like these can hardly be disputed on empirical grounds, but then what do these viewpoints actually mean in a classroom setting?[13] Or, to give another example, constructivists often say that one should draw up an inventory of pupils' pre-knowledge in order to be able to start the teaching from there. However, again, what does that mean in practice and how can one do so appropriately? And then what does appropriate mean in this context?

Gravemeijer (1994) describes the design and construction of an actual teaching-learning sequence as theory-guided bricolage. This indicates properly that it involves a mixture of both theoretical considerations and practical and particularly also creative teaching and writing abilities. Viennot (2001) talked about the importance of *critical details* in research on teaching and learning. This applies in particular also to the actual design of teaching activities and actions. If the teaching activities are not designed and performed properly, the underlying theoretical conceptions may turn out to be of little practical relevance.[14]

Hypothetical scenario

In our own work we have adopted the concept of a *hypothetical scenario* or hypothetical teaching-learning trajectory (Klaassen, 1995). In such a scenario the researcher predicts and theoretically justifies in great detail the expected teaching-learning processes. Such a scenario plays several roles in our research. Firstly, it forces the researcher to make his didactical knowledge, expectations and theoretical perspective explicit in detail and thereby *empirically testable* (see the box below for an example). It also plays a role in the preparation of our participating teachers. Even though they may have been involved in the development of the teaching-

[11] Such a view justifies both the aims of the teaching-learning sequences as well as the basic pedagogical and didactical methods one is using. In the PhD theses mentioned earlier, the term 'problem-posing approach' reflects such a view.
[12] Here we have to consider that, in our view, design research studies should make a contribution to a larger goal, i.e., changing a curriculum in a certain direction.
[13] For, as we all know, adopting a constructivist view of learning only indicates some global perspective on how to teach. Thus the often used phrases 'constructivist teaching strategies', or 'constructivist teaching sequence' as such, are largely meaningless without detailed descriptions of why what is meant by them in practice.
[14] Such critical details may even have to do with the actual wording of teaching activities (see also Klaassen, 1995) and actions of the teacher, the adequacy of the conceptual analysis that is made, the learning steps that are considered to be possible for pupils, the way in which teaching activities really prepare for and are prepared by one another, and so on.

learning sequence, it makes them clearer about *what* they are expected to do and, in particular, *why* they are expected to do it.[15] But foremost, the scenario is a *research instrument*. It enables the researcher to observe precisely where the actual teaching-learning process deviates from what he or she expected. And thus it enables the researcher, even though heavily involved in testing his or her own expectations, to do so in a sufficiently valid and controllable way.

Example

To give an idea of what I mean by 'empirically testable', let me present – and after that reflect on – a small piece of a scenario taken from the thesis of Vollebregt (1998) on the introduction of a particle model. It concerns activity 12 of her teaching sequence.

Scenario
Activity 12 – The value of the model developed so far

Why this activity?
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 pupils, they are encouraged to reflect on the value of the model developed so far. The aim of the activity is to establish pupils' opinion 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.

Classroom scenario
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 really existed. If the latter argument does not arise, 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 previously asked whether the balls existed or could be seen. Probably, many pupils will only find the model really worthwhile if 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 make them more convinced. Most pupils will probably think that they will change their mind if they can actually see the balls.

Why the next activity?
After the previous discussion, many pupils will want to know whether the balls can be seen in order to become more convinced of their existence. The aim of the next activity (Activity 13 – Forming an opinion about the existence of the particles: the case of Brownian motion) is that pupils establish that, although balls cannot be seen through an ordinary microscope, the motion

[15] In fact, we have found it necessary to make a distinction between a *researcher scenario* and a *teacher scenario*. The latter is a more or less diluted version of the first. It describes the teaching activities and the main lines of teaching and expected pupils' reasoning, but not in such detail that the scenario is experienced as a straitjacket.

of much bigger smoke particles is indeed a new indication of their existence. During the next 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.

Reflection

What does this small example show? First, you can see how the chosen didactical perspective (i.e., a problem-posing approach) has been worked out in detail. Second, that the researcher made the aims of, and relation between, her teaching activities explicit. And third, how the teaching activity is supposed to develop in the classroom. This also involves explicitly the teaching actions that the teacher is supposed to perform (thus the critique that research on the design of teaching-learning sequences does not involve the teacher is not valid for this type of research). This scenario is still full of expectations (in the first version primarily based on common sense as well as on relevant research literature) and uncertainties about what pupils may come up with. These expectations can be tested and revised, so that in the final scenario a reasonably complete account can be given of the arguments pupils may bring forward. By ‘reasonably complete’, we mean that the main arguments brought forward are taken into account, as should have become apparent from *saturation effects* in our analysis of the respective classroom protocols of several research cycles.

Data gathering and interpretation

Of course, this does not go without difficulties. The data to be gathered during the try-out are largely qualitative: transcribed interviews, written answers to open questions, transcribed protocols of video and audiotapes. In general, various methods are necessary to enable proper triangulation. This creates the danger of an unmanageable and un-interpretable amount of qualitative data (Dede, 2004). Our scenario is now instrumental not only in deciding on *which* data to *gather,* but also on how to *select* and *interpret* the data. In this respect, our research scenario provides essential guidance, as it enables us to focus in particular on those moments where something unexpected or something crucial happens, or where we felt uncertain about what to expect.

As argued elsewhere (Klaassen & Lijnse, 1996), the interpretation of classroom discourse is an underestimated problem. Particularly with respect to the interpretation of pupils’ utterances, it is important to be explicit about the reference frame from which this is done. Do we interpret them top-down, that is from the point of view of whether they give the ‘correct’ scientific responses, i.e., do we interpret them from *our* scientific perspective which often results in attributing all kinds of misconceptions to them?[16] Or do we try to do our utmost, as I think we should, to

[16] Again, this may need some clarification. Let me give one example. It is well known that in the field of mechanics pupils have a lot of learning difficulties that are usually described as due to misconceptions or alternative conceptions. In both cases, this description implies that what pupils usually say about motion is incorrect. But is that really true? If, for example, pupils say that a force is needed to maintain steady motion, what does their utterance really mean?
If we interpret such an utterance ‘top-down’, from *our* viewpoint of physics, then we cannot do other than conclude that they have a misconception. But such an interpretation does not tell us what

interpret them bottom-up, i.e., from *their* perspective, which means that, as long as they speak about the experiential world that we share with them, we will agree with most of what they say (Klaassen, 1995).

The well-known philosopher Dennett (1992) writes that to interpret people properly, it is necessary to take the *intentional stance*. That is, we have to regard people who make utterances as rational acting persons, who have beliefs, desires and other mental states that have to do with intentionality. Thus, in our case, we have to adopt the view that pupils and teachers are reasonable rational persons, who say reasonable things in view of the circumstances and all the evidence available. So one should try to put oneself in the places of pupils and teachers, and interpret what they say as far as possible from the perspective of what we ourselves would have said in their position in the same situations. Starting from *common ground*, one should be able to make a reasonable *coherent* story of what has been going on in a classroom, not just interpreting students on the basis of disconnected incidental utterances as, for example, is done in questionnaires, but by connecting all the evidence available into a reasonable coherent story, implying that we seem to understand the actual teaching-learning process in sufficient detail.

Try-out

Another aspect that always shows up when dealing with design research has to do with the design of the experimental try-out. In how many classes and with how many teachers should one do so? In my opinion, the answer to this question has to do with what kind of result one is aiming at. When one is dealing with the didactics of a really innovative approach, and we are therefore conducting a really innovative teaching experiment, I would say that an in-depth try-out, in an experimental situation that is *as ideal as possible*, is the appropriate design to provide the necessary information. And by ‘ideal situation’, I mean a try-out with few (indeed often only one will do) specially selected experienced teachers in only one or two of their classes, to make as sure as possible that, on the one hand, the actual didactical process will follow as closely as possible the intended path, and, on the other hand, that no unwanted discipline problems or other disturbing factors will interfere. When such a first try-out has provided sufficient in-depth insight into a possible successful teaching-learning process, then, in subsequent experiments, more and ‘more nor-

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they really mean by their utterances. Therefore we have to try to interpret them ‘bottom-up’, i.e., to try to interpret them from *their* point of view. And maybe we should then conclude that what they are really trying to say is that, in order to maintain motion in daily situations, you have to make some kind of effort – a belief with which we completely agree, of course, and which is no misconception at all.

This is not to say, of course, that we may never say that pupils may have misconceptions. In particular, if one has taught mechanics, and in the final test pupils are still relating steady motion to a net force, then one has to conclude that the teaching has not been successful in reaching its aims. But for the development of a teaching approach in which one tries to build properly on what pupils already know, one has first to ascertain what they already believe and how they express their beliefs.

mal' teachers may be involved, so that the research emphasis may shift, on the one hand, to more general (and even quantitative) results as far as the learning of pupils is concerned, and, on the other hand, towards the *learning processes of teachers* with respect to the new didactics, and thus also with the teaching of that didactics. Again in a subsequent phase, even larger scale comparative studies may be carried out, but then we are no longer dealing with design research as such, but with the evaluation of its products.

Trackability

A particular problem with design research is its replicability. Of course, each teaching experiment is a one-time event, and it can never be reproduced in the same way. A teaching experiment deviates, in this respect, essentially from an experiment in physics. So, what can we nevertheless learn from it? To the extent that design research is qualitative in nature, the norms and principles of qualitative research can be applied (Gravemeijer, 1994). Reliability refers to the absence of accidental errors and is often defined as reproducibility. For qualitative research this means virtual replicability. Here the emphasis is on 'virtual', because it is important that the research is *reported* in such a manner that other researchers can *reconstruct it in principle*. Or, in other words, it should be reported so candidly that it justifies itself, and that the research experience can be transmitted to others to become like their own experience (Freudenthal, 1991). This is aptly expressed by the term 'trackability', because trackability can be established by reporting on failures and successes, on the procedures followed, on the conceptual framework used and on the reasons for the choices that were made.

It may be clear that the scenario (as discussed above) has a crucial role to play in this process. In fact, fellow researchers must be able to retrace the learning process of the design researcher in order to be able to enter into a discussion (Gravemeijer, 1994). Just like the partners within the research project (internal validity), the research community must be in the position to come to inter-subjective agreement (external validity). Only then can we say that we are making a contribution to the field of *public* didactical knowledge, referred to above.

3 The products

Exemplary teaching materials and teacher guides

Now, what are the outcomes of such research? First we have concrete products, i.e., empirically tested *exemplary* teaching materials, in combination with detailed teacher guides, that include detailed descriptions of exemplary teaching-learning processes, as well as of remaining important bottlenecks, within the overall context of the final scenario.

However, the actual final scenario still includes the teaching activities and is thus susceptible to the critique of Tiberghien (2000), who remarked that the design of teaching activities for each domain of physics is an endless task, thereby suggesting that this is not the level our research should aim at. And even though one could say that the scenario has survived several empirical tests, its direct applicability is restricted to the particular teaching sequence it describes.

Domain-specific didactical theory and didactical structure

For the reasons outlined above, I therefore prefer to make a distinction between a scenario and a domain-specific didactical theory. The latter is, in a sense, a reflective meta-level version of the former. It describes, discusses and theoretically justifies the necessary learning and teaching steps to be made for the topic under concern, in terms of *demands* for, and *characteristics* of, successful teaching activities and actions. Such a theory also makes comparisons with other approaches, and describes advantages and disadvantages of the respective approaches together with paradigmatic examples, interactions, crucial steps, and so on.[17] A summary of the essential stages in, and characteristics of, such a didactical theory could be termed a viable *didactical structure* for the topic under concern. Examples of such content-dependent didactical structures are given by Lijnse and Klaassen (2004). Without going into any detail in discussing these structures and their quality now, I only want to remark that the structures essentially reflect, as they should, the views (i.e., a problem-posing approach) within which they have been designed and tried out.

Domain-independent didactical structure

That still leaves the question of the transferability of such a theory and structure to the teaching and learning of other topics. To answer that question, we have to deal with the somewhat paradoxical situation that we have to abstract from the domain-specific aspects of what deliberately intends to be a domain-specific theory, trying to formulate its essential aspects in terms of content-independent characteristics. The latter may apply both to didactical phases as well as to characteristics of the knowledge or skills under consideration. Figure 2 shows an example of what such a more general didactical structure might look like.

This structure depicts the kind of domain-specific didactical structure that results if we abstract from the specific domain it refers to (in this case the introductory teaching of a particle model), and try to characterise the teaching process in terms of more general ‘knowledge levels and motives’, which, of course, would have to be described in more detail to be fully understandable. General structures of this sort may function as useful guidelines to start thinking about the development of other teaching-learning sequences from the same viewpoints.

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[17] Again just one illustrative example. The introduction of the particle model as done by Vollebregt (1998) starts by describing the macroscopic behaviour of gases. That is a choice which can be disputed. Millar, for example, would prefer to start otherwise, by focussing on solids (personal communication). In my opinion, it would be a worthwhile aim of didactical research and theories to enable us to make such choices on more rational grounds than only as a matter of personal *opinions.*

Thus we may conclude that design research provides a hierarchy of outcomes that, on the one hand, fill the level of content-specific didactical knowledge, and, on the other hand, may fulfil a bridging function between general educational theories and educational practice (Figure 3). It is thus this hierarchy of outcomes of design research that has to ensure both its practical applicability as well as its theoretical growth – the more so as these outcomes are concerned not only with the learning of pupils, but also of teachers. Nevertheless, their larger scale application in practice is certainly not self-evident. One should not expect this to take place as a one-time implementation, but much more to result from a long-term gradual dissemination process.

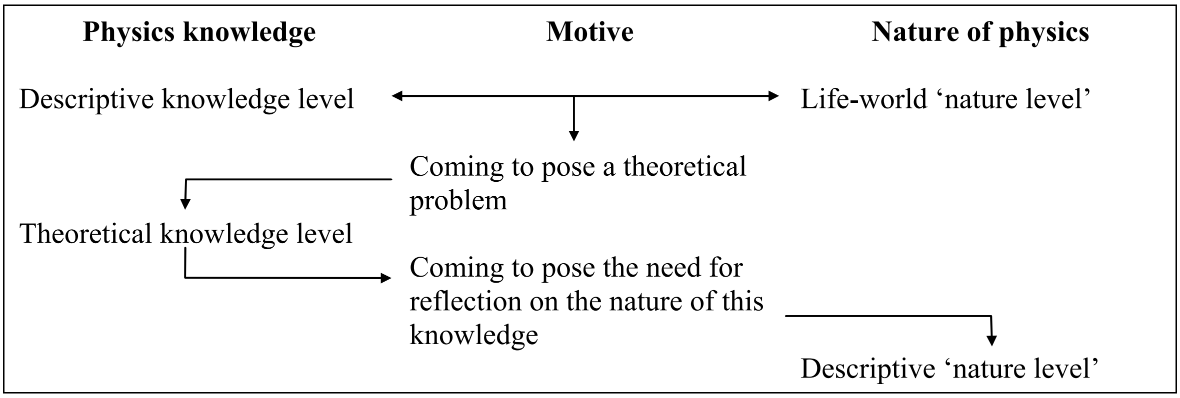

Figure 2 – Level structure of a problem-posing approach to the introduction of a theoretical model.

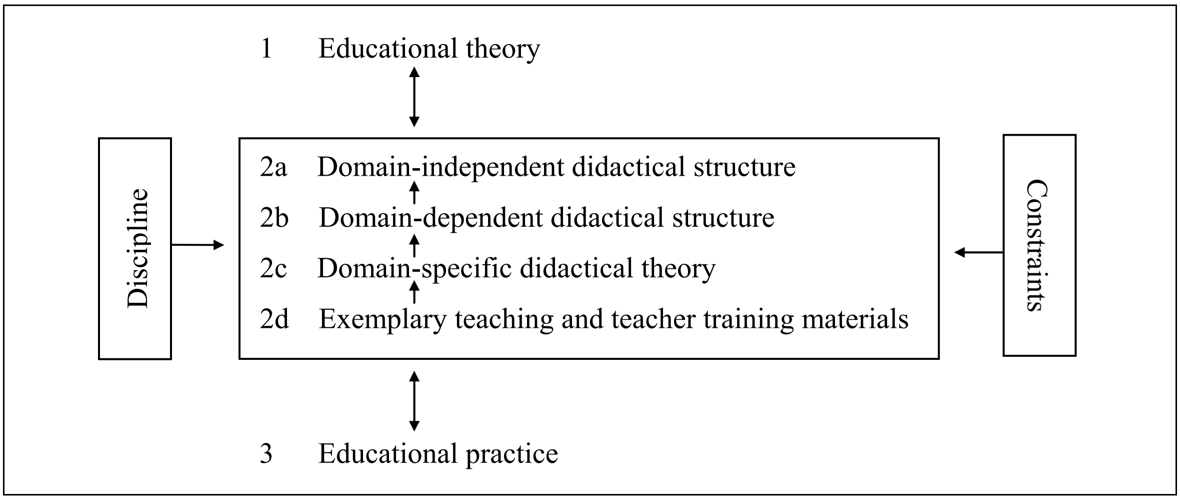

Figure 3 – The outcomes of design research fill the level of content-specific didactics and, at the same time, function as a bridge between general educational theories and educational practice.

The nature of a didactical theory

It might be worthwhile, in this respect, to say a few words about the nature of a didactical theory, as this differs essentially from the nature of scientific theories that we, as natural scientists, are used to.

It should be noted that the predictions which a didactical theory and structure make are to be understood like the teleological explanations (based on *reasons*, rather than *causes*) which we give of human thought and action (Klaassen, 1995). These render someone's behaviour intelligible to us, because they describe his behaviour as being governed by the basic standards of rationality he shares with us. They are, because of their appeal to rationality, description and explanation (rationalisation) in one.

The aim of improving didactical structures is not the same as the aim of improving empirical theories in the physical sciences (and physics in particular). Theories of the latter kind aim at a vocabulary containing concepts with precise conditions of application and at a closed system of strict laws in which those concepts are related, such that the occurrence of events can be predicted and explained with maximum precision.

A didactical theory, however, cannot aim at that. For a didactical theory essentially deals with *mental* concepts such as belief, desire, meaning, intention, and so on. And because those mental concepts only have application against a background of rationality, they resist incorporation into a closed system of strict laws. A didactical theory does not predict or explain by recourse to a system of strict laws, but by an appeal to rationality. The aim of improving a didactical theory thus cannot be to eventually arrive at 'the ultimate' didactical theory. There is also, however, no need for such an ultimate didactical theory. What matters is whether a didactical theory is 'good enough', whether it serves as a valuable guideline for understanding and guiding what goes on in actual classes. In each of these classes, however, the teaching-learning process will without doubt meander in a somewhat different way around the main path predicted by the didactical theory.

Progress in didactical theories?

This nature of didactical theories has important consequences for the question of whether the described way of working might result in didactical progress, as regards both didactical theory construction and didactical practice. As didactical theories are rooted in underlying educational views, in my view such progress should be possible as long as we stay within a particular view on science education. If so, design research makes it possible to improve didactical practice, by enabling didactical change in a particular direction. Because of the nature of didactical theories, however, what might count as progress within a certain perspective may not be considered progress from another. Even comparisons between well-operationalised didactical systems and theories are hard to make, and are seldom convincing to the not-already-convinced. Nevertheless, the more we know about detailed teaching-learning processes, the better we may be able to discuss the advantages and disadvantages of specific theories and approaches, and this could improve the rationality of our decisions.

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10

Didactical structures as an outcome of research on teaching-learning sequences?[1]

Abstract

This chapter describes 'didactical structures' as a possible outcome of research on teaching-learning sequences. Starting from an explicit didactical perspective, in this case a so-called problem-posing approach, the research emphasis is on the didactical quality with which this particular perspective can be put into classroom practice in the teaching and learning of a certain topic. This is done by a process of developmental research, in which a research scenario, as a detailed prediction and theoretical justification of the hypothesised teaching-learning process, plays a crucial role. Three empirically supported didactical structures resulting from such work are described, which have been developed for the solution of different content-dependent didactical problems. By reflection on these structures, more general structures and features are abstracted that enable transfer of the outcomes to the didactics of other topics. Finally, the issue of what these results can offer to the development of a more general didactical theory is discussed.

Introduction

Much work has been undertaken, often as a follow-on from studies identifying students' conceptions about science topics, to develop teaching-learning sequences that represent research-inspired improved ways of teaching these topics (Driver, 1989; Driver & Oldham, 1986; Leach & Scott, 2002; Lijnse, 1994). In our opinion, however, it is doubtful whether such research has as yet made available preferred ways of teaching a topic, or well-argued comparisons of particular teaching approaches.

This conclusion can be drawn from the fact that in the international research literature little information is published about teaching-learning sequences (Gabel, 1994; Millar *et al*., 2000; Tobin & Fraser, 1998). Communication is also made more difficult by the fact that the teaching materials developed are mostly only available in local languages. If they are published at all, details about them can often only be obtained from publications in local journals aimed at teachers. A case in point is, for example, the introductory teaching of a particle model. Even though much work on this topic has been done in several countries, one cannot say that a common research-based opinion has resulted (CLIS, 1987; Meheut & Chomat, 1990; Johnston, 1990; Lijnse *et al*., 1990; Vollebregt, 1998).

What seems to be apparent from much of the literature is that science education

[1] This chapter is a slightly edited version of the original publication in the *International Journal of Science Education 26*(5), 2004, pp.537-554. Copyright 2004, Taylor and Francis Ltd. Permission to reprint this article has been requested.

research does not so much aim to develop content-specific didactical knowledge, possibly to be described as small-scale theories, as to contribute to (if only by simply applying) general educational and/or psychological theories (see, for example, Duit & Treagust, 1998). We regret this ‘flight from content’, because a level is thereby skipped that we consider necessary for making *didactical progress.* The missing level is that of describing and understanding what is, or should be, going on in science classrooms in terms of content-specific interactions of teaching-learning processes, and of trying to interpret them in terms of *didactical theory* (Lijnse, 2000). If one attempts to interpret what is going on in science classrooms directly in terms of such general (learning) theories, one immediately faces the problem that, on application, such theories only result at best in heuristic rules. Such rules simply cannot guarantee that the teaching process that is supposed to be governed by them will have the necessary *didactical quality.*

However, research on actual teaching-learning sequences is seldom published in enough detail to make this problem really come to the fore (see, for example, Leach & Scott, 2002), probably because it is generally felt that it is the necessary personal freedom and competence of teachers that make sequences work in practice. The more so as it is mostly believed that, even if specific aims are agreed, there exists no ‘best way’ of teaching a topic.

Although we agree to a large extent with these opinions, we also believe, however, that such points of view underestimate the difficulty of putting more general theoretical ideas into adequate practice and, consequently, that we should not overestimate the competence of teachers in this respect (see, for example, Klaassen & Lijnse, 1996). And, apart from that, although a best way of teaching a topic may indeed be an illusion, we do think that some ways are better than others, and therefore that it is worthwhile searching for evidence of how and why that is the case and for means that enable the *didactical quality* of such teaching sequences and situations to be expressed and discussed. In this chapter it is argued that the concept of ‘didactical structure’ might provide a further step towards fostering deeper discussions of this kind about didactical advantages and disadvantages of particular ways of teaching a topic. Therefore, we will first describe three examples of didactical structures that have resulted from our research on teaching-learning sequences and discuss, finally, the extent to which such structures might help us in communicating more accurately about their didactically relevant aspects.

1 Views on science and science teaching and learning

In general, the design of teaching-learning sequences should start by making explicit and justifying one’s view on teaching and learning, on science and on science education (Millar & Osborne, 1999). The reason for this is, of course, that neither education nor science are value-free processes and, thus, that we can only communicate and discuss our research results properly if they are placed within and judged from the value-laden context in which they are obtained. These value-laden choices are not only reflected in the goals that one wants to reach, but also in the ways they are aimed at.

For the design of teaching sequences, for example, in principle it may make a difference whether one starts from a receptive, behaviouristic, discovery or information-processing view on learning, to name just a few influential views from the recent past (Duit & Treagust, 1998), even though such differences may, in didactical practice, turn out to be much smaller than expected. Regarding views on learning, much attention has been attracted recently by constructivism. In our opinion, the didactical relevance of that view boils down to the rather trivial idea that 'new knowledge is constructed on the basis of already existing knowledge' (Ogborn, 1997). As such, this view does not relate directly to a view on teaching, as the construction process of the learner always takes place, irrespective of how he/she is being taught. However, if one wants to prevent a learning process that results too quickly in a *forced* conceptual development that is full of misconceptions, or, in other words, if one adopts the view that teaching should result in something like real understanding, it seems necessary to allow students ample freedom to use and make their constructions explicit, for example, by means of social interactions with the teacher and/or peers (freedom from below), and at the same time to carefully guide their construction process in such a way that it results in the aims that one wants to reach (guidance from above).

Finding an adequate balance between this necessary freedom from below and the equally necessary guidance from above lies at the heart of our didactical research. It means that one tries to guide students in a *bottom-up* teaching-learning process, starting from *common ground* (i.e. starting from shared, and known to be shared, ways of thinking about the world), by designing teaching activities that are to gradually create places in students' conceptual apparatus that the concepts and skills one wants to teach can occupy. In that sense, we can give content to the phrase 'construct new knowledge on the basis of already existing knowledge'.

At first sight, this view seems to represent nothing new, as is clear from many reports about 'constructivist science teaching' (Leach & Scott, 2002; Scott *et al*., 1992). In our work, however, we differ in two major aspects from these reports. Although we take 'educational constructivism' in the aforementioned sense as a first starting point, we do not adhere to the 'alternative framework' movement. In our view, students' beliefs about their experiential world are, in general, largely correct, which implies that, if properly interpreted, we can always find common ground to start from in our teaching process (Klaassen, 1995; Klaassen & Lijnse, 1996). As far as cognitive learning is concerned, we think it best to think of science learning as a process in which students, by drawing on their existing conceptual resources, experiential base and belief system, come to *add* to those (with accompanying changes of meaning).

What we think needs to be added to this picture, as a second starting point, is that if this process is to make sense to them, students must also be made to *want* to add to those. Or, in other words, students should at any time during the process of teaching and learning see *the point* of what they are doing.[2] If that is the case, the

[2] The following quotation, as reported by Gunstone (1992), shows that this is not a self-evident

process of teaching and learning will probably make (more) sense to them and it then becomes more probable that they will construct or accommodate new knowledge on grounds that they themselves understand. An approach to science education that explicitly aims at this, we call *problem posing.* The emphasis of a problem-posing approach is thus on bringing students into such a position that they themselves come to see the *point* of extending their existing conceptual knowledge, experiences and belief system in a certain direction. Thus formulated, the second starting point also seems rather trivial, and indeed it is. Since in themselves both starting points do not give any further detailed didactical guidance, the real *non-trivial* didactical challenge lies, as already mentioned, in the quality with which they can be put into practice – the more so as such an approach asks for a considerable change in didactical contract (Tiberghien, 2000) as compared with what teachers and students are mostly used to.

In correspondence to this and in analogy to what Freudenthal (1991) writes about mathematics, we might say that we see science as a human activity and that, consequently, science teaching should guide students in '*scientificalising*' their world, instead of trying to transfer scientific knowledge as a ready-made product. Freudenthal speaks in this context about a process of *guided reinvention* that students have to participate in, adding that for its design it might be quite inspiring to look into the history of invention.

Our point of view of developing a problem-posing teaching-learning approach along these lines thus asks for a thorough didactical analysis of common-sense and scientific knowledge, as well as of their relation. How can we design a conceptual teaching pathway that is divided into such steps that, in a teaching situation, students are meaningfully able and willing to take them, building productively on what they already know and are able to do? Can we make students ask or value questions that, on the one hand, make sense to them and that, on the other, ask for the development of (possibly adapted) new ideas and scientific concepts to be taught that provide an answer to their questions?

That means that, for them, the concepts to be reinvented will function for a particular purpose, and that the reasons for their construction and acceptance are di-

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condition.

In the following typical example, the student (P) has been asked by the interviewer (O) about the purpose of the activity they have just completed.

P: He talked about it ... That's about all ...
O: What have you decided it [the activity] is all about?
P: I dunno, I never really thought about it ... just doing it – doing what it says ... its 8.5 ... just got to do different numbers and the next one we have to do is this [points in text to 8.6].

In addition, Gunstone writes: "This problem of students not knowing the purpose(s) of what they are doing, even when they have been told, is perfectly familiar to any of us who have spent time teaching. The real issue is why the problem is so common and why it is very hard to avoid." As a remedy, much emphasis has been laid on fostering students' general meta-cognitive knowledge and skills. Students should learn to learn. Without wanting to argue about the value of this emphasis, in our approach we adopt the additional view that it should also be clear to students on content-related grounds why and what they are doing.

rectly derived from that functioning. In doing so, apart from being guided, knowledge construction within this problem-posing approach is, in a sense, similar to the process of professional knowledge construction within science itself. Knowledge is constructed (under guidance) for a certain purpose. And it is accepted by those who construct it to the extent that it functions productively for that purpose.

In our opinion, we may roughly distinguish four main purposive orientations in which scientific knowledge may function: practical (learning to cope in everyday life); theoretical (learning to understand nature); technical/industrial (learning to design technical artefacts or industrial products); and societal (learning about science and society). These purposive orientations are related to different views on (the relations of) science, technology and society, and thus their possible adoption in science curricula requires an explicit view on science education that has to be matched with a particular view on the social and pedagogical role of education itself. For the design of teaching-learning sequences this means, in general, that such sequences will be developed within one or more particular orientations that are to be made functional for students.

2 Methodology

Before presenting some results of our research on teaching-learning sequences more explicitly, we first want to say some words about our methodology (Gravemeijer, 1994; Klaassen, 1995; Lijnse, 1995, 2003). In our work, we may distinguish between three levels of working. We develop *teaching-learning materials* for teachers and students. However, we do not just write them rather intuitively as textbook writers usually do. In fact, we develop them in parallel with a *scenario.* This scenario *predicts* and theoretically *justifies* in detail the teaching-learning *process* as it is *expected* to take place and *why* it is expected to happen in that way. This relates in particular to the interaction of teaching and learning activities. Thus we may consider the scenario to be a *hypothetical* domain-specific didactical theory *(in statu nascendi)* that can be tested and revised. In developing that scenario we take great care to make a thorough didactical analysis of the content to be taught, and to try to interpret teaching activities through the eyes of the students. We also put much emphasis on the connection between the teaching activities and on the role of the teacher in making these activities 'work'. Does the previous activity really prepare for the next activities, and is the next activity really sufficiently prepared for by the previous activities? Or, in other words, can the expected teaching-learning *process* really be considered *coherent* from the perspectives of students and teacher?

The development of a scenario asks for a mixture of didactical analysis, intuition and creativity, and for the use of teacher craft knowledge as well as of theoretical heuristics and reflection. Gravemeijer (1994) writes in this context about 'theory-guided bricolage'. In fact, in developing a scenario, we precisely try to fill the didactical gap we have already mentioned.

In the try-out of the teaching sequence, the scenario functions as a detailed research *instrument* that guides our observations and interpretations of the teaching-learning process. An adapted version of the scenario is used in our teacher preparation. Such an adaptation appeared to be necessary to reduce the risk that the teacher may experience the scenario too much as a straitjacket. After one or two cycles of testing, the scenario and teaching materials may have reached the stage that they can be considered ‘good enough for practical purposes’ (i.e., for teaching practice).[3]

Then the interrelated conceptual and content-related motivational pathway (i.e., the main steps to be taken and stages to be gone through by teacher and students), as derived from the final scenario, are reflected upon and summarised in what we might provisionally call a possible *didactical structure* for the topic at hand. For this process of abstraction we have no definite *a priori* criteria, as it involves a process of ‘theory in the making’.

In our empirical procedure, we think it is essential not only to focus on the learning of the students, but in particular also on the learning of the teacher. In fact, this learning of the teacher could also be reflected upon in terms of a didactical structure of the content-specific didactics at hand. A theoretical reflection on the learning of both students and teacher, in relation to the scenario as developed and the chosen starting points, leads to the final *didactical learning process of the researcher.* An adequate report of that might be considered the main scientific outcome of our didactical research, in the sense that it should reflect progress in didactical knowledge that is both theoretically grounded and empirically supported.

3 Examples of empirically tested didactical structures

Before we describe some examples[4], it should be kept in mind that the structures presented are short-hand descriptions of the respective scenarios and teaching materials. In fact, the extent to which they are really comprehensible for those who are not familiar with the latter can be questioned. Nevertheless, they are attempts to communicate essential didactical aspects; that is, to show how research-based sequences attempt to solve a particular didactical problem. At the content-specific level they represent feasible empirically tested new answers to practical didactical problems. These answers have been developed within an explicit didactical perspective, as regards purposive orientations and views on teaching and learning science, and can thus be discussed and judged on their consistency and appropriateness from

[3] In the development of our scenario we focus on the description of an empirically tested optimal ‘average’ teaching-learning process. In practice, the actual process will always deviate from the final scenario to a lesser or larger extent. We call it ‘good enough’, or to have sufficient didactical quality, if the empirical test shows that the anticipated process is feasible for both teacher and students and that the expected learning effects are satisfactorily obtained. This implies that actual unexpected deviations do not essentially disturb the scenario and can be handled adequately by the teacher. It also means that the students in general are able to make the necessary learning steps, so that no lasting conceptual blockages or major misinterpretations result.

[4] It should be kept in mind that the structures will be described here only in summary. A full description and empirical justification of each structure is given elsewhere (Klaassen, 1995; Vollebregt, 1998; Kortland, 2001).

that perspective. In that sense they represent examples of didactically new 'good practices', in which not only results of relevant educational research are taken into account, but are also extended and enriched at the level of didactics.

An introduction to radioactivity

A first example concerns an introduction to radioactivity within the regular compulsory curriculum for lower ability students of age 15.[5] A lesson sequence of approximately twelve lessons (of 50 minutes each) was designed, primarily within a *practical* orientation. Figure 1 summarises the final resulting structure of our approach. This structure consists of two columns, the first focusing on the knowledge to be taught, and the second on the motives to be developed that should drive the learning process.

Our first goal was to design a teaching approach that would not result in the usual conceptual confusions regarding radioactivity (Eijkelhof, 1990; Klaassen, 1995). The structure therefore starts at students' life-world knowledge about radioactivity. At this level radioactivity is something mysterious and vague, as no difference yet exists between what is meant scientifically by the terms 'radioactive substance' and 'radioactive radiation', and so no distinction can be made between 'irradiation' and 'contamination'. The first major didactical problem then consists of making it meaningful for students to learn about these distinctions. So their life-world knowledge is productively used to encourage them to formulate, within the chosen context, a practical problem (i.e., 'how can one make something radioactive?'). Students come to formulate this question when their expectation that something that is 'irradiated' (e.g. an apple placed for a long time in the neighbourhood of an object that according to them 'is radioactive') will itself have become 'radioactive' turns out to be false.

The bottom-up character of the sequence is further reflected in the fact that it does not start from theoretical knowledge about atoms and nuclei (nor necessarily end with it), as is usual in textbooks for this topic, but, in order to tackle the problem, first develops a level of empirical generalisations, in terms of 'irradiation', 'radioactive substance', 'radiation' and 'contamination', that are sufficient to understand the potential dangers and corresponding protection measures in some situations.

The problem-posing character of our approach is, in particular, reflected in the interrelation of the motives and knowledge that are to be developed. A general characteristic of our approach is the role of a 'global motive', relating to the sequence as a whole, connected to a series of 'local motives' that motivate its main phases. It should be noted that the principal focus of the structure under concern is on the transition from the life-world level to the qualitative and quantitative levels of empirical generalisations, by means of making students themselves come to pose a practical problem that is meaningful for them, that they want to solve. It is this

[5] This indicates that research in didactics is not only content specific but also, to a certain extent, system specific.

characteristic, together with the way in which that problem is subsequently solved, that can be considered a major didactical result, when compared with other approaches in which the conceptual difficulties involved are either neglected or tackled inappropriately.

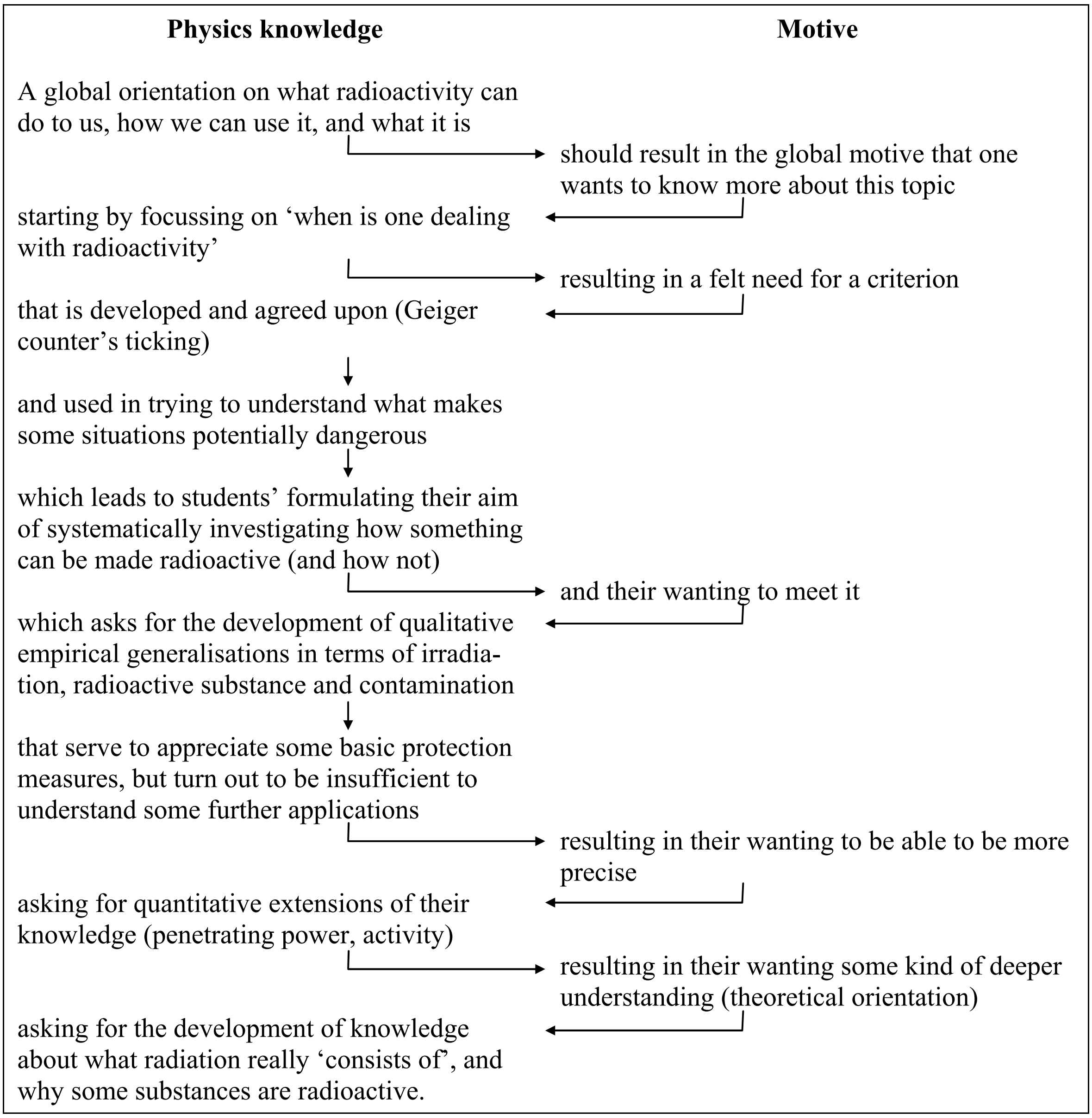

Figure 1 – A didactical structure for a problem-posing approach to the introduction of radioactivity.

In this didactical structure, we may distinguish the following phases:
- Phase 1: Orienting and evoking a global interest in and motive for a study of the topic at hand.
- Phase 2: Narrowing down this global motive to a content-specific need for more knowledge.
- Phase 3: Extending the students' existing knowledge, in the light of the global motive and the more specifically formulated knowledge need.

- Phase 4: Applying this knowledge in situations for which the knowledge was extended.
- Phase 5: Creating, by reflecting on the developed knowledge, a need for a theoretical orientation.
- Phase 6: Developing, within this orientation, further theoretical knowledge.

Phases 2 and 5 represent one of the main points of a problem-posing approach. Such phases appear not to be present in the teaching cycles published in the literature (Abraham, 1998). Those cycles deal almost exclusively with cognitive learning, even though it is also often noted that one should not forget the importance of motivation. In our approach, however, both are considered together and integrated from the start.

These phases relate to particular didactical functions that have to be fulfilled in such a way that they assure the necessary coherence in the activities of the students. This asks from the teacher that he/she function not only at a cognitive level, but also regularly at a didactical meta-cognitive level. It is this latter teaching activity that has appeared not only to be very unusual for teachers but, in spite of the examples in the scenario, also very difficult.

In reflection on the structure of Figure 1, we may also come to a more general, and therefore probably more transferable, representation of the didactical structure. This description focuses more on characteristics of the knowledge involved, albeit still in a rather global way. In fact, three ways of talking about radioactive phenomena are described in Figure 2, each with its specific concepts and associated ways of explaining. The didactical challenge is to make learners move meaningfully downwards through this three-level structure by making them see the point of using and developing new concepts, in order to meet new explanatory interests. The transferability of the structure in Figure 2 lies in the fact that it provides a way of thinking that may also be applicable to the development of a more detailed didactical structure for the teaching of other topics.

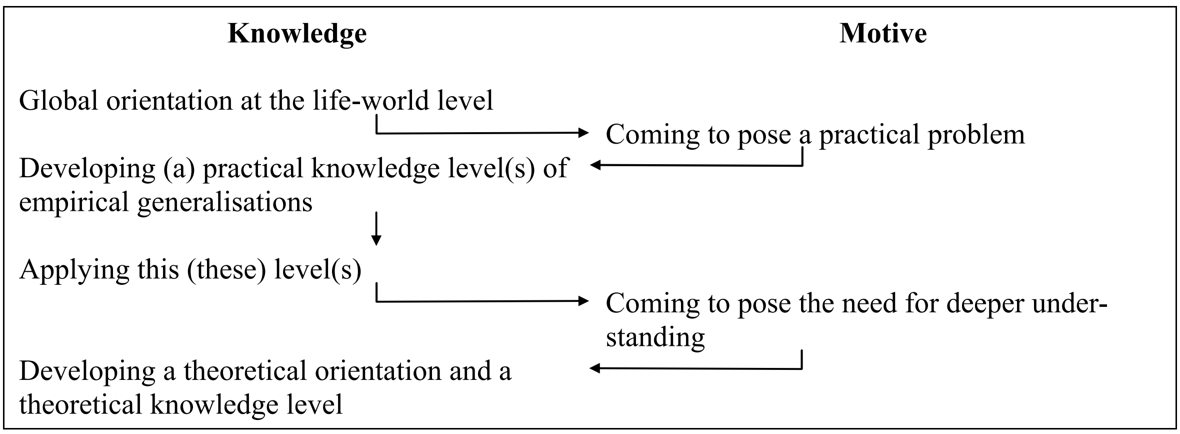

Figure 2 – Level structure of an introduction to radioactivity.

The interrelated teaching of an initial particle model and the nature of particle models

A second example of a didactical structure that resulted from a tested scenario comes from the work of Vollebregt (1998). In a sequence of nine lessons (of 65 minutes each), Vollebregt designed a problem-posing approach for the introduction of an initial particle model as part of the compulsory physics curriculum for higher ability students of age 16. Thus, in her work, the development of a *theoretical* orientation and the subsequent development of theoretical model-based knowledge address the standard problem of explaining macroscopic properties of matter in terms of a submicroscopic model, in a way that is meaningful and understandable for students. Much research has shown this to be a didactically difficult challenge, which we do not claim to have solved. However, we do claim that we have achieved more insight into a possible didactical way out.

In the sequence, a theoretical orientation first has to be evoked. As a starting point for that, we have chosen previously taught descriptive level knowledge of the macroscopic behaviour of gases, which is then problematised on the basis of the idea that in physics one tries to come to ever deeper understanding by asking evermore ‘why and how come’ questions. This latter idea can be interpreted as a still rather vague element of the ‘life-world level’ with respect to the nature of physics, worded in a rather undifferentiated fashion, which is used here productively together with the rather obvious idea that the ‘machinery of things’ can often better be understood if one looks for what they are made of. It is the difficult task of the teacher to use these ideas together with what students already know about the behaviour of gases to guide them in coming to ask the question of what gases are actually made of, and in then presenting a first intelligible germ of a particle model, in terms of criss-cross moving small balls, that puts students on the right track for a further fruitfully guided modelling process in which the germ is extended into a first ‘real’ particle model (Lijnse, 2000).

The initial particle model in terms of moving balls is then further developed by students in order to explain the macroscopic gas laws (e.g. Boyle’s law). This extended model is also still formulated in terms of moving balls. The *prima facie* plausible methodological maxim not to assume more than necessary (Occam’s razor) can then be invoked to make students wonder if the particles need to be balls and, more generally, what properties can be attributed to the particles and on what grounds. In doing so, after a while, students easily come up with the question of whether their modelling process is leading to the ‘right’ answer, which provides the natural opportunity to go further into methodological, epistemological and ontological aspects of what they have been doing. Thus, in reflection, some ‘rules of the modelling game’ can be made explicit and illustrated, which could perhaps be interpreted as part of a kind of ‘descriptive’ level of knowledge about the nature of physics/modelling.

This structure thus shows the interesting feature of two distinguishable, although reflectively coupled, learning processes that, by means of the middle motives column, drive each other.

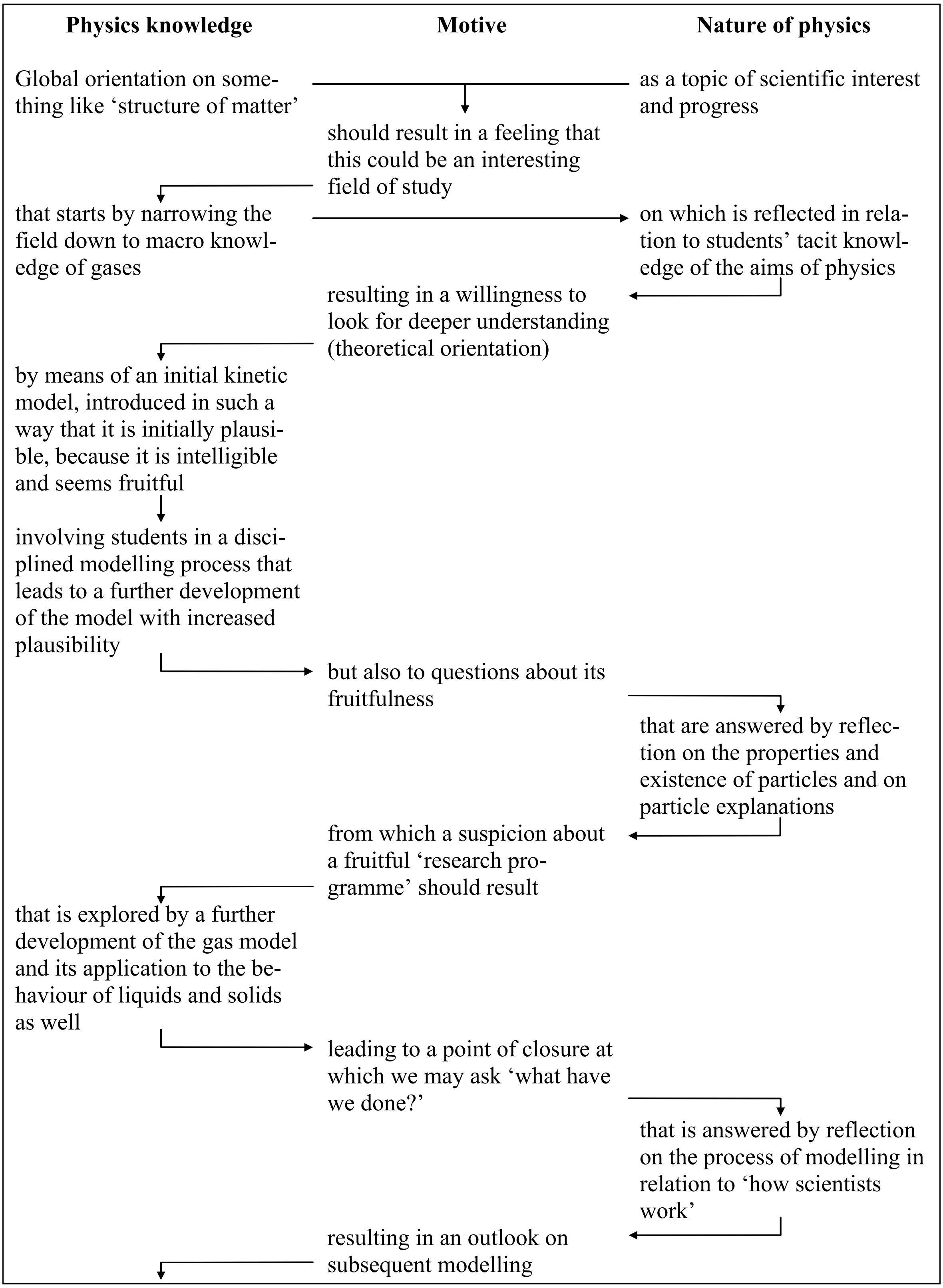

Figure 3 – A didactical structure for a problem-posing approach to a modelling introduction of an initial particle model.

The first column deals with the teaching of a particle model and the third with teaching about the nature of physics, in particular about the nature of particle models. This reflects the fact that, in developing this sequence, we aimed at *both* objectives. However, the interrelatedness of both learning processes was not anticipated in any detail and came out in reflection afterwards. We find this an important outcome as it may represent a natural way in which teaching about the nature of science could be integrated into the teaching of science itself, so that it might not appear as a strange add-on. As such, this can be recognised as an attempt to meet Duschl's (2000) challenge, formulated as follows: "The need for school science programmes to focus on the various public understandings of the nature of science is an important educational goal", for which "the challenge is to design instructional sequences and learning environment conditions that help pupils become members of epistemic communities". Figures 3 and 4 show what a didactical structure for such a sequence might look like. This aspect comes even more clearly to the fore when we compare these structures with the two-column structures of Figures 1 and 2. The latter represent only a motives-driven knowledge development, in line with the single main teaching objective of the sequence, thereby leaving its epistemological and methodological aspects implicit.

Another aspect that emerged in this structure is that ideas about conceptual change theory, or about using analogies, were not applied as such but nevertheless appeared to be present to a large extent in a natural way in our teaching scheme. In fact, in retrospect, this is rather obvious as a problem-posing approach is trying to evoke and elaborate content-related motives for students to ground the development of their knowledge. This implies that ideas like intelligibility, plausibility and fruitfulness (i.e. the status descriptors in conceptual change: Hewson & Lemberger, 2000), come not only self-evidently to the fore in the didactical process, but also in a 'natural way' in view of the progress made in the learning of content matter. The same remark applies to a large extent to the concept of 'learning demand' as introduced by Leach and Scott (2002).

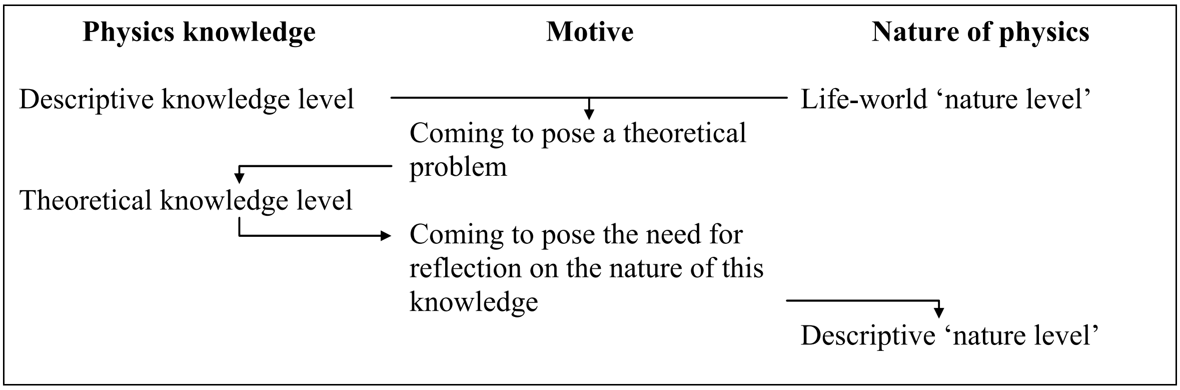

Figure 4 – Level structure of a modelling approach to the introduction of a particle model.

In terms of a level structure we may now come to the scheme of Figure 4. This level structure was not yet available as an *a priori* instrument in developing our teaching sequence, so this description does not fully apply to the teaching sequence as developed. Moreover, this teaching sequence only gives a first start for the filling of the given levels. In further sequences, this has to be further elaborated and extended. Within this structure, we may again distinguish several didactical phases that, although different in detail, are to a large extent similar to those already formulated (see also later).

The interrelated teaching of subject matter knowledge and general skills

In the structures of Figures 3 and 4 both teaching-learning processes are reflectively coupled, so that the second evolves more or less at a meta-level with respect to the first. Nowadays, however, science education is also expected to contribute to the teaching of general skills that are independent of any specific science content matter. This constitutes another serious didactical problem that asks for further attention. The crux of the problem consists of what it means if one wants to teach skills like ‘problem solving’, ‘investigating’, ‘information processing’, and so on (Millar & Driver, 1987; Taconis *et al.*, 2001). Do they need to be taught at all? And, if so, how can we best do it, and in particular how does this teaching then relate to the teaching of subject matter content? Kortland (2001) has tackled this problem for the ‘general skill’ of decision making, which is formulated in our compulsory attainment targets for lower ability students (age 15) as being able to present an argued point of view. Kortland studied decision-making skill in relation to teaching about the environmental waste issue.

This ten-lesson sequence (of 50 minutes per lesson) was set within a practical orientation and dealt with the question of how to deal best with waste household packaging from an environmental point of view. In a problem-posing approach, this has led to a content-dependent didactical structure as represented in Figure 5. After an orientation on personal decision-making about household waste, at the level of using both life-world knowledge and decision-making skills, students come to the recognition that they first need to know more about waste household packaging. Then, in using this knowledge to present their point of view about a decision-making situation, they come to realise that it is not obvious at all what it means to present a ‘well-argued’ point of view. Thus, in reflection, a (still contextualised) number of heuristic rules are made explicit that may help them to structure and check their reasoning. Again, this set of heuristic rules is termed a descriptive level of decision making, as it describes, organises and makes explicit the intuitive procedures used so far. Thus, from Figure 5, again a content-independent level structure can be abstracted, as shown in Figure 6.

The first four teaching phases as identified by Kortland (2001) are identical to those already formulated. However, the next two phases are now described as follows:

- Phase 5: Creating, in view of the global motive, a need for a reflection on the skill involved.
- Phase 6: Developing a (still contextualised) meta-cognitive tool for an improved performance of this skill.

The structures of Figures 5 and 6 consist of three columns, because we deal again with two coupled teaching-learning processes, related to the two main objectives of the sequence. However, the nature and relation of both processes is now quite different from that in the previous case.

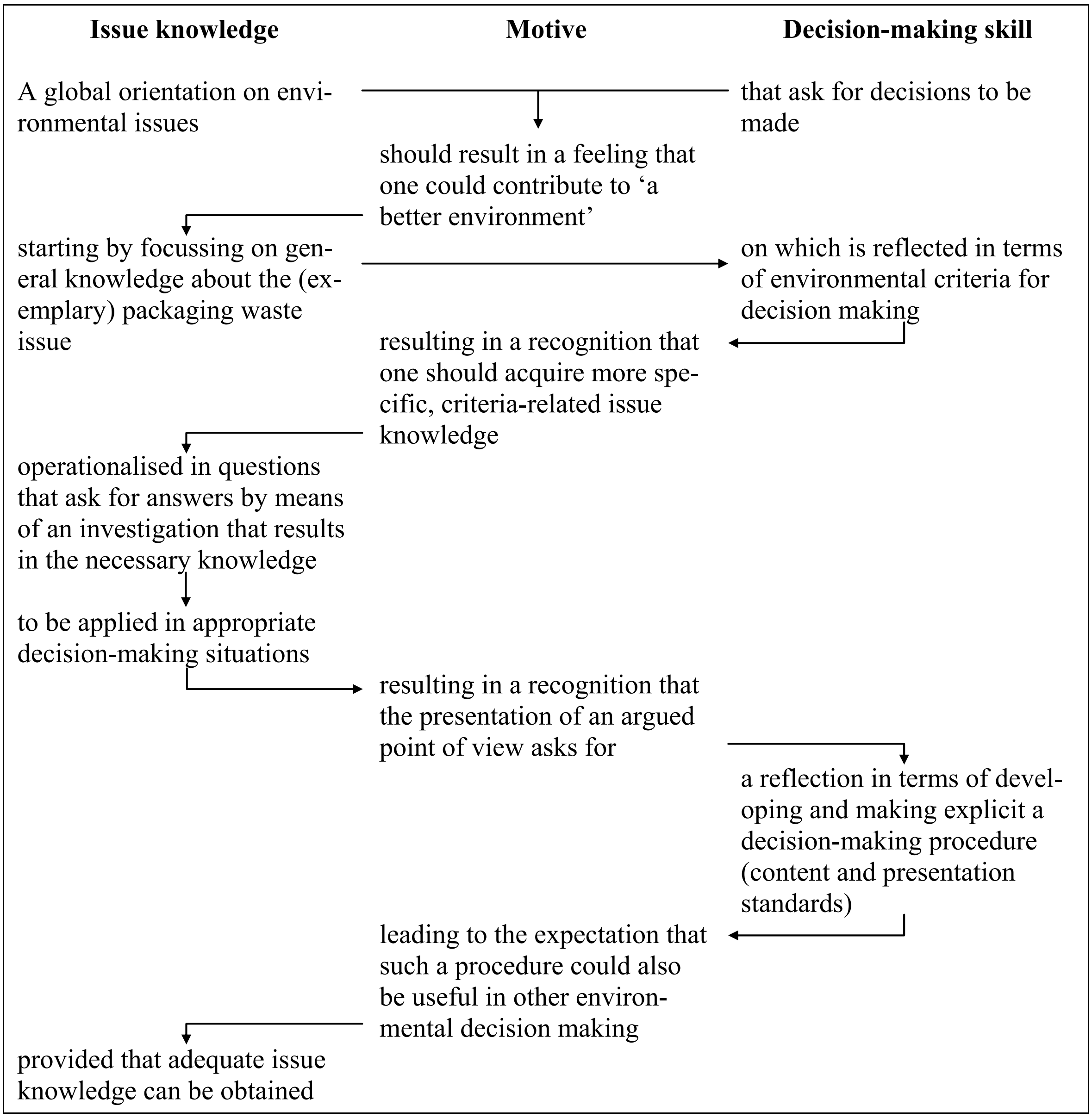

Figure 5 – A didactical structure for a problem-posing approach about decision making on the waste issue.

Both teaching-learning processes start at the everyday level and, by starting from common ground, make productive use of what students already know. As far as the skill of decision making is concerned, this means that students are not so much learning to make decisions, because they do this all the time. But it still seems worthwhile to teach them, in situations for which this appears to be relevant, how to reflect explicitly on the quality of their decision-making procedure. To guide this reflection process, a meta-cognitive heuristic 'tool' may be useful. In the structure presented, this tool is still developed within the context of the waste issue (i.e., within the knowledge context at stake). However, in a series of subsequent decision-making modules, thus as a curriculum strand, this tool may gradually be decontextualised towards a tool on decision making itself.

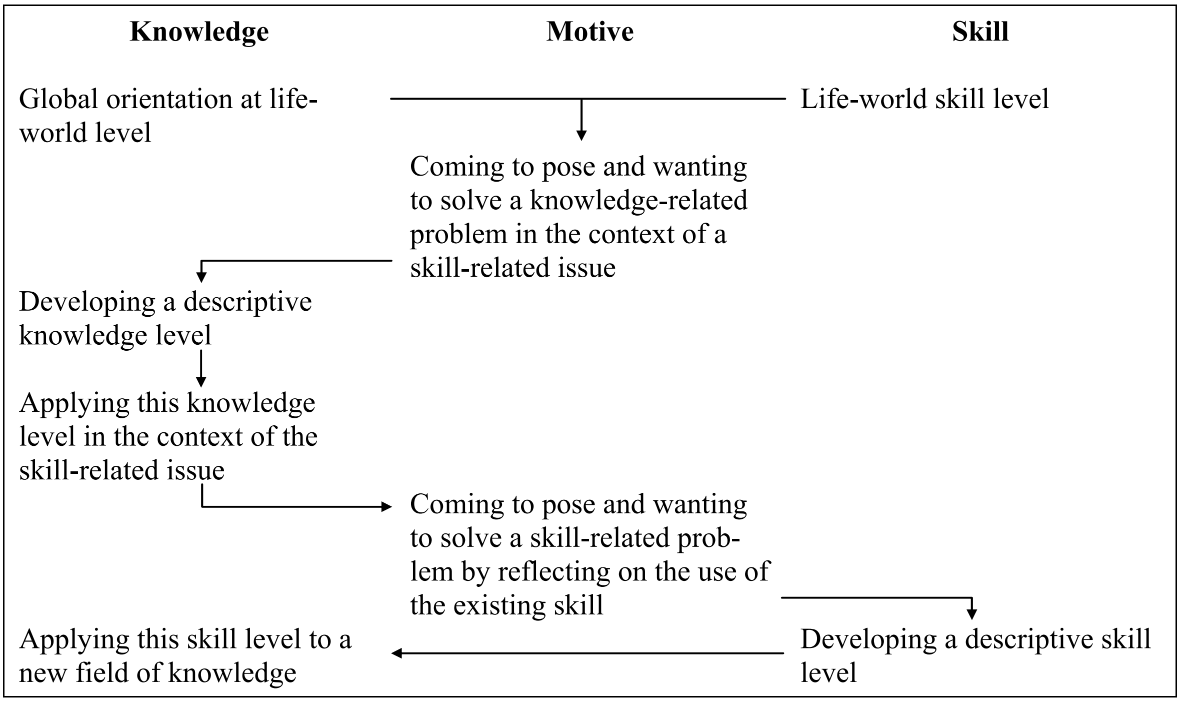

Figure 6 – The level structure of a problem-posing approach to the interrelated teaching-learning of content matter knowledge and a general skill.

This concludes a brief description of our work on didactical structures so far. Both characteristics, the level structure and the teaching phases, could perhaps be interpreted as elements of a more general didactical theory that needs to be worked out further.

4 Reflection

What, then, may we conclude from the discussion above? The examples given are intended to represent research-based ‘good practices’, in which results of relevant educational research are not only taken into account, but also extended and enriched at the level of didactics. As we have already noted in the introduction, it is precisely the filling of that level that is too often skipped in science education research, or left as an impossible task for teachers. The given structures, together with their respective scenarios, may not represent the best way of teaching the topics under concern, but, we would argue, they do represent better ways (in the sense that it is probable that more students will understand and like what is taught in the intended way). And thus they contribute to making available new didactical knowledge at a level that is in principle applicable for teachers and may help them in solving some of their problems. The structures and scenarios themselves do not describe the necessary learning processes of teachers. However, in our research, these learning processes are also documented, and could be described in similar structures, which would represent didactical structures for the learning of content-specific didactics.

The level structures are an attempt to generalise our procedure. In doing so, we focus on characteristics of the knowledge and skills involved, but still within a didactical context. The usefulness of this level of abstraction, however, is certainly a matter for discussion. Nevertheless these level structures may contribute to the development of a more general didactical language and theory that is applicable to more situations (didactical structure, didactical contract, didactical knowledge and/or skill level, didactical phases and didactical functions, purposive orientations, problem-posing approach, and so on) – even though these concepts have not yet been worked out or discussed here in sufficient detail.

In the introduction we mentioned the problem of communicating the outcome of research on teaching-learning sequences, and in particular their didactical quality. So does the framework described here provide useful opportunities in this respect? In our opinion it does. For example, if results of research on teaching-learning sequences were more fully reported in terms of underlying didactical structures, on the one hand as operationalisations of explicit basic starting points, and on the other as advisory teaching-learning trajectories, a deeper comparison of the didactical pros and cons of the respective approaches could take place. The more so if more attention was also paid to criteria of didactical quality. Such criteria can in fact be abstracted directly from the considerations already described, such as:

- What is the didactical problem under concern and what is offered as a solution: what are the basic views that underpin the didactical structure; are those views adequately operationalised; and does the resulting structure really make a new and explicable contribution to solving the problem?
- Can the designed teaching-learning *process* really be considered *coherent* from the point of view of the students: are the students provided with functioning global and local motives; are the students able to construct (in a guided and cooperative manner) the expected concepts; and do the students reach the intended aims to a sufficient degree?
- Is the teaching process sufficiently manageable for the teacher and does he/she succeed in solving unexpected problems in the spirit of the anticipated scenario: does the teaching process start from a proper interpretation of common ground; do the teaching activities really prepare for, and are they really prepared by, each other; does the teacher provide sufficient construction space for the students and does he/she manage to interact with them productively; and is he/she able to monitor the learning process at a meta-cognitive didactical level?

If criteria such as these got sufficient attention in the communication of research on teaching-learning sequences, we think it could give a clearer view of their didactical quality, which would make it easier to build on them in future research.

Tiberghien (2000) remarks that the design of teaching situations 'for each domain of physics can be an endless task'. In her research she therefore focuses on the design of teaching situations that are representative of a set of situations, by making use of more general characteristics of physics knowledge. This reflects an important dilemma. We agree that the outcome of didactical research cannot (only) be at the level of teaching situations themselves, although, in the end, the question of quality can only be answered at that level, as each general research outcome that asks to be applied in practice is in danger of not being applied properly. Our approach of empirically supported scenarios and 'didactical structures of a certain topic' is another attempt to deal with this dilemma. Of course, such structures, together with their worked out scenarios, cannot succeed without the experience and craftsmanship of good teachers. As such, they are not teacher-proof nor can they guarantee that the learning process of each individual student will be successful. However, they do provide even experienced teachers with new didactical insights that can improve their teaching considerably at key points. That is why they can improve the learning and teaching of a certain topic, in the sense that more students will understand and value, in the intended way, what they have been taught. If more research-based didactical structures (or whatever one wishes to call them) became available, then from mutual comparisons and discussions more didactical progress would be possible.

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