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THE RELATIONSHIP OF THEORY AND PRACTICE IN DESIGNING, IMPLEMENTING AND EVALUATING TEACHING SEQUENCES: Learning from examples that don't work

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Abstract: This paper is about the process of designing and evaluating teaching sequences. It presents a framework to inform the design and evaluation of science teaching (Ametller, Leach and Scott, 2007); the use of the framework is illustrated through discussion of examples. Three short teaching sequences (around 5 hours) are used to exemplify the use of the framework in the design and evaluation of teaching. Each teaching sequence was developed to address conceptual content in the lower secondary school (age 11-13). The sequences addressed Electricity, Plant Nutrition, and Modelling (Physical and Chemical) Change. Each sequence was implemented by at least three teachers. Students' learning was evaluated using diagnostic questions for conceptual understanding, and compared with that of similar students following the school's usual teaching approach. Data about the implementation of the teaching were collected through video recording, and teachers were interviewed before and after implementation. The Modelling Change teaching sequence was the first to be developed. Students' performance, and teachers' reactions to this sequence, fell considerably short of our design intentions. Significant changes to the design approach were therefore made for the Electricity and Plant Nutrition sequences, which were very well received by teachers, and resulted in statistically significant learning gains by students (Leach et al., 2006). The Modelling Change sequence is therefore presented in more detail, to illustrate how the framework can inform judgements about the success or failure of attempts to design science teaching.

Key words

John Leach & al

The problem addressed in this paper

How can theoretical insights about teaching and learning science be drawn upon to inform the design, implementation and evaluation of science teaching?

This question has received a good deal of attention in the science education research literature, which contains some reports of interventions that have been broadly successful in achieving their aims. However, it is often difficult to establish what precisely is being claimed in papers that report successful teaching interventions, and how these claims might be built upon in subsequent work. To illustrate the problem, we will use an example from our own and colleagues' recent research (Leach, Ametller, Hind, Lewis and Scott, 2006), though similar points could be made in the context of many other published studies. We designed three short teaching interventions, and attempted to show how perspectives on learning, and the findings of previous empirical studies, had been drawn upon in the design (Leach and Scott,

2002). The teaching sequences were implemented and evaluated. The evaluation evidence shows that, for two of the teaching interventions, students who followed the designed teaching achieved *significantly better conceptual understanding on some measures* than comparable students who had followed a school's usual teaching approach. Furthermore, *teachers not involved in the design of the teaching* used the teaching sequences and achieved improvements in their students' learning similar to those achieved by the teachers who collaborated on the design of the teaching. However, the third teaching sequence did not succeed in meeting its design intentions in several key respects.

What can be concluded from studies such as this which address the design and evaluation of teaching sequences? Do the successful results show that the underlying perspective on science learning is correct? Alternatively, can we conclude that two of the three specific teaching approaches were successful, and should therefore be widely adopted?

Neither of these claims are supported by the available evidence. All three teaching sequences were informed by the same perspective on teaching and learning science, yet only two out of the three succeeded in meeting their design intentions. Furthermore, a cursory review of the literature shows that very different teaching approaches have been justified on the basis of similar perspectives on learning, and also that rather similar teaching approaches have been developed based upon quite different perspectives on learning. As Robin Millar argued nearly 20 years ago, general learning theories such as constructivism do not have direct implications for specific methods of teaching (Millar, 1989). Furthermore, the evidence from a study like ours shows that a particular teaching approach was successful for a relatively small group of students following a particular curriculum, taught by a small number of individual teachers, working in a small number of schools in England. It does not show that the teaching approach is better than others that teachers or researchers have designed to tackle broadly similar content. There is no evidence that the teaching approach could be used in other national or institutional contexts.

So what *can* be claimed on the basis of studies like ours? Without a clear answer to this question, it is hard to see how the research community will be able to draw upon each others' results to establish reliable knowledge about the design of teaching.

The first section of this paper presents a framework for describing the process of designing science teaching. The use of the framework is illustrated with reference to the design of a short teaching sequence which uses a simple particulate model to explain various physical and chemical change processes ('*Modelling Change*'). Evidence about the implementation and evaluation of this (and the other two) teaching sequences is then presented. The *Modelling Change* teaching sequence failed in significant respects to meet its design intentions, whereas the other two teaching sequences were broadly successful. The paper concludes with a discussion of how the framework can be used to interpret findings from the evaluation of teaching sequences which succeed, and fail, to meet their stated aims, thereby enabling more precise communication about the outcomes of research on the design and evaluation of science teaching.

A framework for describing the design of science teaching and the findings of design research studies

Why another framework?

Science teachers, curriculum designers and textbook writers are all involved in the process of designing science teaching. Normally, however, this process is intuitive and the rationale for design decisions is not made explicit. In the academic literature, several lines of research and scholarship can be identified which make explicit various choices and problems that are encountered in designing science and mathematics teaching. Typically, a general perspective on learning is presented and implications for the design of teaching are set out in very general terms. This can be seen in Engle and Conant's (2002) work on *productive disciplinary engagement*: a sociocultural perspective on learning is used to justify general features of the pedagogy such as making students' work *accountable* to others. We have described such general guidance about pedagogy as being at a *large grain size* (Leach & Scott, 2008). However, in designing science teaching (or indeed any subject teaching) there are many decisions about both content and pedagogy that need to be made, which are at a *fine grain size*. In the case of science education, an obvious example is the detailed treatment of content: when introducing the idea of electric current, *precisely* what ideas are going to be presented to students, and in what order?

There are some accounts in the literature which address design decisions at a fine grain size (e.g. design research in North America, Brown, 1992; developmental research in the Netherlands, Gravenmeijer, 1994; the theory of didactical situations in France, Brousseau, 1998; educational reconstruction mainly in Germany; Duit, Komorek and Wilbers, 1997). However, in spite of well theorised positions on the part of designers, actual design decisions are often not made explicit (Méheut and Psillos, 2004). There are examples of literature which address in some detail how teaching sequences are evaluated through a systematic and iterative process (e.g. Brown, 1992; Cobb et al., 2003; Lijnse, 1995). Brousseau (1998) has developed a *theory of didactical situations* which develops tools which can be used

in the analysis of mathematics teaching. However, in each of these cases more attention appears to be given to explaining why particular teaching approaches are effective in *post-hoc* evaluation, than explaining the design rationale for teaching in advance. More could be done to inform decisions at a fine grain size in terms of perspectives on science learning. We have developed our framework with the intention of addressing more precisely the ways in which perspectives on learning are drawn upon to inform the design of science teaching *a priori*, and its evaluation *a posteriori*.

The framework draws upon a social constructivist perspective on learning science in formal settings (Leach and Scott, 2003). This perspective was used to inform the shape of the teaching sequences at a large grain size. In addition, empirical evidence about teaching and learning particular scientific content is drawn upon; the social constructivist perspective was used to interpret this evidence. Two design tools were developed to guide the design process, which draw upon both theoretical and empirical insights from research and scholarship on teaching and learning science to inform design decisions about the teaching sequence at a fine grain size. We will describe the social constructivist perspective and the two design tools in the following paragraphs, showing in each case how these informed the design of the teaching sequences.

A social constructivist perspective on learning science in formal settings

Vygotsky's sociocultural view of learning suggests that higher mental functioning (such as conceptual understanding) in the individual derives from social life (Vygotsky, 1978, p. 128). Language and other semiotic mechanisms provide the means for concepts to be talked through between people on the social (or inter-mental) plane – be these scientific concepts, or the concepts that are used in everyday communication. Scientific knowledge is developed as a result of social interactions between scientists who work together to build explanations for evidence about the physical world. Ideas like *momentum* are developed because scientists agree upon a particular way of modelling some aspect of the physical world. Everyday conceptions are also developed through

social interactions: children grow up surrounded by talk which suggests that things 'burn away to nothing', and pictures where balloons filled with air 'floats upwards on the string' (rather than where the inflated balloon should be drawn falling to the floor).

The process of *internalization* (Vygotsky, 1987) is where individuals appropriate and become able to use for themselves (on the intra-mental plane) conceptual tools first encountered on the social plane. Central to this view is the continuity between language and thought. It is not the case that language offers some 'neutral' means for communicating personally and internally generated thoughts: language provides the very tools through which those thoughts are first rehearsed on the social plane and then processed and used on the intra-mental plane. Wertsch (1991; p. 46) has made the point that the Vygotskian view is limited in that there is no recognition of the *different* forms of inter-mental functioning which occur on the social plane. He has turned to the work of M.M. Bakhtin for the additional tools needed to develop the Vygotskian account. Bakhtin draws attention to the fact that different modes of discourse are used in different parts of society and he refers to these as *social languages*. All of these social languages 'are specific points of view on the world, forms for conceptualizing the world in words, specific world views, each characterized by its own objects, meanings and values. As such they all may be juxtaposed to one another, mutually supplement one another and co-exist in the consciousness of real people...' (Bakhtin, 1934/1981, p. 292).

The *scientific* social language is that which has been developed within the scientific community, and is based on the use of specific concepts such as energy, mass and entropy. It involves the development of models which provide an account of phenomena in the natural world, and it is characterized by certain key epistemological features such as the development of theories which can be generally applied to different phenomena and situations. However, it is not the case that 'anything goes' in the generation of scientific knowledge, as this knowledge should, in principle, be consistent with empirical evidence about the material world. Scientists are not in a position to create their social language in isolation from empirical data.

There is also an *everyday* social language that learners are constantly exposed to. If learning science is conceptualized as ‘learning to talk in new ways’ or ‘learning to talk science’ (Lemke 1990), then the act of learning might appear deceptively straightforward: isn’t it the case that the student simply learns how to talk about familiar phenomena in new ways? However, as indicated there is strong evidence that some aspects of scientific social language are strikingly difficult for learners to use and understand. The notion of internalization is used to address this issue. Internalization does not simply involve direct transfer of ‘ways of talking’ from the social to the personal plane. There must be a step of personal interpretation, where the individual comes to a personal understanding of the ideas encountered on the social plane. That is, individual learners must make sense of the talk that surrounds them, relating that talk to their existing ideas and ways of thinking. Learners must reorganize and reconstruct the talk and activities of the social plane.

Implications for the design of science teaching

This social constructivist perspective brings together the social-interactive and personal-sense-making parts of the learning process and identifies language as the central form of mediational means on both social and personal planes. It draws upon sociocultural approaches in conceptualizing learning in terms of developing a new social language, and in identifying epistemological differences between social languages. It draws upon evidence about alternative conceptions (which often have been generated through studies carried out in a personal constructivist framework) in clarifying the nature of the learning required by students in order to make personal interpretations of the social language of science.

We believe that this social constructivist perspective on learning science in formal settings has implications for the design of teaching sequences at a large grain size. The social constructivist perspective foregrounds a requirement for teaching to introduce the scientific social language to students on the social plane of the classroom. We have portrayed this process as *staging the scientific content*, the ‘staging’ metaphor emphasising the key role of the teacher in orchestrating a the classroom in order to present

scientific content to an audience. The teaching must also support students in the process of *internalisation* of scientific content that has been encountered on the social plane of the classroom, with the teacher having a key role in diagnosing student difficulties and assisting their performance through structured interventions. Finally, the teaching must provide opportunities for *handing-over* responsibility to students for using new ideas for themselves.

We will now present two design tools that have been developed from this specific framework in order to inform decisions about the design of science teaching at a fine grain size. We use the term ‘design tools’ to refer to concepts which draw upon theoretical perspectives on teaching and learning, and the products of empirical research on teaching and learning, to inform decisions about the design of teaching. The word ‘tool’ is used to underline the fact that theoretical insights are brought to bear on the design process, and real work on the design is then carried out. We think that design tools have much in common with *humble theories*, which according to Cobb and colleagues ‘are accountable to the activity of design. The theory must do real work. General philosophical orientations to educational matters – such as constructivism – are important to educational practice, but they often fail to provide detailed guidance in organising instruction.’ (Cobb et al., 2003; p. 10-11).

Design Tool 1: Learning demand

Learning demand (Leach and Scott, 2002), was developed to help to identify the conceptual aims of science teaching at a fine grain size. Learning demand draws directly upon the social constructivist perspective in that it involves making a comparison between two social languages, namely the social language of school science and the social language that school students are likely to use when discussing phenomena and events at a given point in their science education. The conceptual basis of explanations of the material world in each social language is identified in terms of ontology, epistemology, and the patterns of reasoning on which explanations are based. These are then compared between the two social languages; learning demands are identified in terms of the different concepts and associated onto-

logy, epistemology and patterns of reasoning used in students' everyday social language, and the social language of school science. The learning demands in a given area of content are then used to identify the precise nature of the content-specific learning that needs to be supported through teaching.

We will now illustrate the identification of learning demands by considering the introduction of explanations of the behaviour of simple series circuits in the lower secondary school. Prior to teaching, students' explanations tend to be based on the behaviour of 'electricity', whereas the physics explanations to be taught in the English curriculum are based upon current, charge and energy: the two social languages have a different ontology. Furthermore, students tend to draw upon different explanations for different circuits, whereas the social language of physics is based on the use of a single explanatory framework: the two social languages have a different epistemology. In addition, students' explanations tend to be based upon a linear causal sequence of events, starting in the battery with events in the resistive components of the circuit following later. By contrast, the social language of school physics describes circuits as integrated systems where events happen at the same time. The social languages of students and school physics are thus based upon different patterns of reasoning.

Design Tool 2: Communicative approach

Communicative approach (Mortimer and Scott, 2003) is a design tool which focuses on classroom discourse and provides a perspective on *how* the teacher interacts with students to develop specific ideas on the social plane of the classroom. The verbal communication in the classroom is described in terms of two dimensions: authoritative/dialogic, and interactive/non-interactive. In authoritative discourse, an authority figure (normally the teacher) controls the direction of the talk, to focus it on one point of view (normally the scientific view). In dialogic discourse, the discourse is open to different points of view, both everyday and scientific. Interactive talk involves more than one speaker, whereas non-interactive talk involves just one speaker. Mortimer and Scott relate the communicative approach to different teaching purposes. For example, authoritative talk is more

appropriate when new meanings are being introduced on the social plane of the classroom, whereas dialogic talk is more appropriate when students' everyday views are being explored. One would therefore expect to see 'shifts' between authoritative and dialogic discourse throughout a sequence of lessons, according to the purpose of the talk (Scott, Mortimer, & Aguiar, 2006).

Design briefs

Design briefs make explicit issues to be addressed in teaching, together with the rationale for addressing those issues. The use of the two design tools provide insights for designers into the conceptual issues that teaching needs to address (at a fine grain size), and the way in which classroom talk might best be organised (at a fine grain size) to support the introduction of new ideas in the classroom, or situations where students are using and internalising new ideas. Other design tools could no doubt be developed which draw on different perspectives on teaching and learning, and focus on other aspects of the design of teaching. Furthermore, it is important to note that many aspects of the design of teaching may not be informed by using these (or, indeed, other) design tools. For example, science lessons are unlikely to achieve their aims in terms of promoting students' conceptual learning if they are perceived as dull by either teacher or pupils, or if the lessons do not meet systemic norms and expectations for science teaching. For this reason, we worked alongside groups of practicing teachers in our work on designing and evaluating science teaching.

The design brief for a piece of science teaching will specify the purposes of the teaching, and the content-specific learning aims for the teaching at a fine grain size. Based on the social constructivist perspective outlined above, the purpose of the teaching at different points in a teaching sequence will include staging scientific content, supporting internalisation, and handing-over responsibility to students.

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 an analogy or developing a model to make plausible some aspect of content
- Using empirical evidence (data, observation, graph) to make some phenomenon or event explicit
- Setting up a conflict to be resolved by students
- Presenting the science view, with a view to building straightforwardly on students' existing understanding
- Differentiating ideas, or contexts, and teaching about the contexts where it is appropriate to use an idea

The design brief will state why a particular pedagogic strategy has been selected to address a particular learning aim, at a fine grain size. For example, the pedagogic strategy *Using empirical evidence* might be selected on the grounds that a learning demand has been identified suggesting that learners are likely to know little about a phenomenon or event prior to teaching, or to hold misconceptions about the behaviour of the phenomenon or event. The pedagogic strategy *Using an analogy* might be selected to make some aspect of a phenomenon or event plausible, when an analysis of learning demands suggests that students find an aspect of the scientific social language implausible.

Design briefs will draw upon a range of insights, including the use of design tools, the outcomes of

evaluations of teaching, the requirements of formal curricula and the professional knowledge of teachers.

Worked examples

Design briefs do not specify particular teaching activities. We refer to sequences of teaching activities that address a design brief as *worked examples*. It is possible to develop many different worked examples to address a design brief. Comparing one worked example with another is not, however, a simple matter. In the first instance, researchers have to be clear that two different worked examples were, in fact, designed to address the same design brief. If this is not the case, then evaluation methods may well be biased towards one worked example ('testing bias'). Furthermore, researchers have to be clear whether they have evidence about the design of a worked example *per se*, or whether their evidence is in fact about the way in which an individual teacher implemented the teaching. It is very difficult to distinguish methodologically between the impact of the teacher and design decisions taking outside the classroom. Nevertheless, when trying to compare worked examples it is very important that researchers clarify whether or not they have evidence about the design itself. Another major difficulty is in presenting evidence to support conclusions about which aspects of a piece of teaching caused particular outcomes in terms of students' understanding. These methodological difficulties are discussed more fully in Leach et al. (2006).

Figure 1: A research evidence-informed approach to designing science teaching

Figure 1, taken from Ametller, Leach and Scott (2007), summarises our approach to the research evidence-informed design of science teaching:

Our portrayal of designing science teaching may appear rather linear: use design tools, formulate a design brief, develop and evaluate worked examples. In practice, of course, the process is more iterative than this. In our experience, early attempts at formulating a design brief as a result of using design tools are normally modified significantly once worked examples have been developed, discussed and evaluated. Differentiating between design briefs and worked examples facilitates discussion about whether a particular piece of teaching addresses its design intentions, or whether the design intentions themselves require modification.

In order to illustrate the difference between design tools, design briefs and worked examples, we will describe the design of some teaching which introduces a simple particle model to account for

aspects of the behaviour of matter at the beginning of secondary education.

Example: using the framework in the design process

Use of design tools

The first task in the design process involved identifying the learning demands for this area of the curriculum. We began by analysing the content in the school science curriculum, which is mandatory for all English students in state schools (QCA, 2007). The part of the curriculum followed by students at the beginning of secondary education (i.e. age 11 – 14) is called ‘key stage 3’ (ks3). At ks3, students are introduced to a simple particular model of matter, and this is used to explain simple physical and chemical change processes. The following aspects of the national curriculum for science at ks3 include content about modelling change processes in terms of a simple particle model of matter:

Classifying materials		
1		Pupils should be taught:
		<i>Solids, liquids and gases</i>
b		how the particle theory of matter can be used to explain the properties of solids, liquids and gases, including changes of state, gas pressure and diffusion
		<i>Elements, compounds and mixtures</i>
e		how elements combine through chemical reactions to form compounds [for example, water, carbon dioxide, magnesium oxide, sodium chloride, most minerals] with a definite composition
g		that mixtures [for example, air, sea water and most rocks] are composed of constituents that are not combined

Changing materials		
2		Pupils should be taught:
		<i>Physical changes</i>
a		that when physical changes [for example, changes of state, formation of solutions] take place, mass is conserved
c		to relate changes of state to energy transfers
		<i>Chemical reactions</i>
g		how mass is conserved when chemical reactions take place because the same atoms are present, although combined in different ways

Figure 2: Curriculum content on modelling change (age 11-14)

The curriculum refers to ‘the particle theory of matter’, but no further account is given about which aspects of that body of scientific knowledge are to be introduced at ks3. In practice, this means that there are significant differences in the way in which curriculum content is presented to students by different teachers, and in different schools. However, the questions used in national tests indicate that the structure of matter is intended to be modelled in terms of hard, tiny balls that do not themselves change, that are in constant motion, and whose motion is dependent upon temperature. Furthermore, a model of atoms as a nucleus and ‘electron shells’ is introduced at ks4 (age 14-16), indicating that subatomic particles are not to be introduced at ks3. No account of bonding between atoms is presented in the official curriculum at ks3, nor in national tests.

We then analysed evidence about the characteristic ways in which pupils, of different ages and at different stages of their science education, explain the nature of matter, as well as the outcomes of studies which evaluate specific teaching interventions. We drew particularly on review articles of this literature (e.g. Andersson, 1990; Driver et al., 1994; Vollerbreght, 1998; Méheut, 1998; Kabapinar, 1999), together with important empirical studies (e.g. Séré, 1986). From this body of existing research, the following characteristic issues in pupils’ reasoning about matter were identified:

- Gases may not be thought to be matter in the same way that solids and liquids are (they have zero or negative mass, they are not involved as reactants in chemical changes where solids or liquids are the product)

- It may not be appreciated that particles are matter – sometimes, matter may be thought to *surround* the particles, particularly in gases
- The *mass*, *volume* and *density* of substances may not be differentiated (solids may be thought to be *heavier* than liquids and gases, large objects may be thought to be heavier than smaller ones)
- Macroscopic properties of substances (e.g. colour, expansion on heating) are ascribed to individual particles (copper sulphate crystals are made of blue particles, the particles in iron expand as a result of heating).
- The macroscopic, observable characteristics of chemical change processes are attributed to particles (e.g. particles change from one kind to another kind, particles appear and disappear)

Based upon our analysis of the content of the ks3 curriculum, and our review of the literature, the following learning demands were identified:

- Coming to appreciate that a simple model can be used to account for the behaviour and characteristics of matter in a wide range of situations. In particular, coming to appreciate:
 - that solids, liquids and gases are all matter, and their behaviour can therefore be accounted for using the same model;
 - the difference between changes which involve a re-arrangement of the bonds between atoms (termed *chemical changes*) and changes which do not involve such a re-arrangement (termed *physical changes*)
 - how macroscopic properties can be explained in terms of sub-microscopic particles, without attributing individual macroscopic properties to the particles;
 - that matter is conserved during physical and chemical change processes; and
 - that if matter appears not to be conserved then an explanation must be sought in terms of changes in particles.

The first learning demand addresses an ontological difference between the social language of students, and the social language of school science. Many students tend to think of gases as ‘different in kind’ from solids and liquids. This has profound implications for their understanding of chemical change processes involving gases. Although students can learn to use chemical equations as algorithms to represent change processes, they nonetheless find the underlying concepts implausible: ‘How can something as solid as wood be made from a reaction between a gas in the air and water?’ The first learning demand also has an epistemic dimension: students have to come to appreciate that the purpose of the particle model of matter is to explain (appropriately to the level of the students) the behaviour of *all* matter in *all* change processes.

We did not use communicative approach at this stage in the design process.

Development of a design brief

The ks3 model of matter presented in the curriculum can be used to provide a simple explanation of the conservation of mass in physical and chemical change processes, and phenomena associated with gas pressure and diffusion. However, it is difficult to see how the model can give a satisfactory account of several of the examples provided in the curriculum (such as the physical differences between solids and liquids, chemical combination, the difference between chemical combination and mixing) given that no explanation of bonding is provided. We wanted to introduce a model of matter to students that is consistent with the model in the curriculum that can explain the change processes specified in the curriculum better than the model in the curriculum, but that does not go too far beyond the model introduced in the curriculum. Furthermore, the designed teaching needed to introduce the model to students in a way that addresses the learning demands specified above.

The teaching was to be used as a revision activity with students aged 14, who had already been taught about modelling the behaviour of matter in terms of particles at an earlier stage in their science education. It is worth emphasising that we did not know

in any detail how previous teaching had addressed modelling physical and chemical change in terms of a particle model. The designed teaching sequence had to be short, in order to allow time for other revision activities. However, this area of the curriculum is widely perceived to be difficult by teachers, and in addition research evidence suggests that the ability of many 14 year old students to use the model to generate explanations is rather limited. Given our lack of knowledge about the content of previous teaching, and the belief by ourselves and the teachers that students may still have a rather limited understanding of this area of the curriculum, it was necessary for the teaching to provide opportunities for the teacher to make formative assessments of students' existing knowledge, and to select teaching activities accordingly. Depending upon students' existing knowledge, this might involve the teacher in brief revision (and some extension) of the previously-taught model, or extensive teaching of the model, together with opportunities for students to practice using the model to construct explanations (with appropriate support).

Therefore, the design brief for the teaching made the following specifications:

The teaching sequence should:

- last for a maximum of 4 lessons (in order to allow time for other revision activities)
- address the identified learning demands

- draw upon a model of matter that can explain the required aspects of the behaviour of matter, but that does not go too far beyond the requirements of the ks3 curriculum

- provide opportunities for the teacher to introduce the model systematically to students (i.e. allow for the *staging* of the content)

- provide teachers with opportunities for making formative assessments of students' existing understanding, thereby enabling them to provide students with opportunities to practice using the model to generate explanations of the range of phenomena identified in the curriculum, with appropriate support (i.e. allow for *supporting internalisation*)

- Provide opportunities for *handing-over* responsibility for generating explanations to students

- provide teachers with guidance as to how teaching activities might be selected and used depending upon students' existing understanding, but teachers with responsibility for deciding how staging, supporting internalisation and handing-over responsibility was to be handled at a fine grain size.

Development of a worked example to address the design brief

We developed the following model of the particulate nature of matter:

Feature of the model	Notes
<u>Matter is made of particles</u> <ul style="list-style-type: none"> • All matter is made entirely of particles. • Individual particles are too small to be seen. • We can think of particles as being like hard, tiny balls that do not change. They are usually drawn as dots or small circles. • There is nothing in between the particles. 	This model reflects the assumptions that appear to underpin questions in the national tests sat by 14 year olds in state schools in England. It does not provide any mechanism for bonding between particles in solids, or attractions between particles in liquids (see below).
<u>The motion of particles</u> <ul style="list-style-type: none"> • The particles are in constant motion. • As you heat particles, they move more and as you cool them they move less. 	This aspect of the model is used to explain phase changes on heating.
<u>The distribution of particles</u> <ul style="list-style-type: none"> • In solids and liquids the particles are packed so closely that they are touching. • In solids the particles are arranged in regular patterns. Each vibrates in a fixed position. • In liquids the particles are arranged irregularly and move from place to place by 'rolling over' each other. • In gases, the empty space between the particles is much larger than the space occupied by the particles themselves. • Particles of a gas in an enclosed space are evenly distributed (because gravity has a negligible effect on them). 	This explains the relative elasticity of solids, liquids and gases, and the big discrepancies in density between solids and liquids compared to gases.
<u>Attractions between particles</u> <ul style="list-style-type: none"> • Any two particles are attracted to each other, but the size of this attraction decreases rapidly with distance. • In a gas the attraction is negligible, except at high pressure and at low temperature when it may cause a gas to condense to a liquid. 	This aspect of the model is often not dealt with at ks3, with the result that pupils are not presented with a mechanism for bonding in solids, or attractions between particles in liquids. The notion of <i>attraction</i> between particles goes some way to explaining bonding without referring to electrons. If inter- and intra-molecular forces are modelled like this, it will be necessary to differentiate the different mechanisms at KS4 in terms of electrons.
<u>Similarities and differences between particles</u> <ul style="list-style-type: none"> • There are 100 or so fundamental particles, called atoms. • Different substances consist of different particles, but all particles of one substance are identical. • A mixture consists of particles of 2 or more different kinds. • A chemical reaction is a re-arrangement of atoms. 	The term 'particle' is used for both atoms and molecules. This use of the word makes it difficult to differentiate the structure of atomic, ionic or molecular giant structures from simple atomic and simple molecular structures.

Table 1: The simple particle model of the structure of matter developed for the Modelling Change teaching sequence

This model draws heavily on the model developed and justified by Vollerbrecht (1998).

The *Modelling Change* teaching sequence consisted of 4 lessons. The purpose of the first lesson was to provide the teacher (and the students) with detailed formative assessment evidence about the level of the students' existing understanding of previously-taught content about modelling physical and chemical change in terms of a simple particle model. Five diagnostic questions, termed 'thought experiments', were undertaken in pairs. Each question presented a

phenomenon, and asked pupils to explain what was happening. In addition, pupils were prompted to illustrate their explanation, imagining what it would look like if the internal structure of the matter could be seen. The purpose of this was to cue pupils to use the particle model that they had already been introduced to during previous teaching. One of the questions is presented in Appendix 1, in illustration.

The five diagnostic questions are based upon different change phenomena. In the terms used in the national curriculum, one of the changes would

be termed a chemical change (i.e. the combustion of magnesium). The other examples either involve no change, or what would be termed physical changes (i.e. compressing air, dissolving sugar, mixing liquids, heating iron). We are aware, however, that this sharp distinction between physical and chemical change is not easy to sustain. Each diagnostic question was designed to assess pupils' understanding around one or more of the learning demands. For example, each question asked about conservation of mass on change, and each question required pupils to use the simple particle model that had already been taught.

Detailed notes were provided for the teacher about the aim of each question, typical pupil responses, and how the ideas raised in the question would be followed up and built upon in subsequent teaching. Students' responses to the five diagnostic questions were used to provide baseline information about their understanding of particle models of the nature of matter in the evaluation of students' learning following teaching.

The lesson concluded with a demonstration activity in which students are asked to watch a beaker of boiling water, to say what they think is in the bubbles, and to ask their parents' opinions. This activity is picked up during the second lesson.

The second lesson begins with the teacher revising and extending features of the particle model outlined above. The model is summarised on a pupil sheet. The teacher then uses the model to explain the appearance of bubbles in boiling water, and to model the combustion of magnesium. Pupils are then presented with another example of a chemical change (involving ionic precipitation), which they are asked to model in terms of particles. The teacher then illustrates how the expansion of iron is modelled, and pupils are presented with a more complex example of physical change to model for themselves, involving a Cartesian diver. Teachers can select from these activities according to the outcomes of the diagnostic questions in the first lesson. The lesson involves the scientific story being staged, with opportunities for the teacher to support internalisation and handing-over. The teacher has considerable autonomy in deciding how each activity is used in terms of staging and handing-over, in order to support internalisation by the students.

The third lesson involves pupils in repeating the thought experiments, with emphasis upon detailed modelling of each change in terms of the particle model that was revised and developed in lesson 2. Guidance about the communicative approach to be adopted by the teacher is provided for each activity. The activities of the second and third lessons require the teacher to use different forms of communicative approach. The intention was that the teacher would use a good deal of *interactive/authoritative* discourse in revising and extending the particle model, with more *interactive/dialogic* discourse in supporting pupils' understanding. A good deal of *non-interactive/authoritative* and *interactive* discourse would be used as teachers demonstrated to pupils how to model change phenomena in terms of particles, with more emphasis on *interactive/dialogic* discourse as teachers supported pupils' attempts at modelling. Notes were provided on each activity about key questions to raise with pupils. However, no serious attempt was made to present the overall communicative approach in the written materials, and teachers therefore had considerable autonomy in determining the design of the lesson at a fine grain size.

The final lesson involved pupils in completing seven diagnostic questions in a test format. These questions include contexts already encountered by pupils in the thought experiments and lessons 2 and 3, as well as new contexts. An illustrative question can be found in Appendix 2.

A summary of the evaluation evidence for the three teaching sequences

We have described the design and evaluation of the *Plant Nutrition* and *Electricity* teaching sequences previously (Scott et al., 2006; Leach et al., 2006), and the sequences themselves are accessible on the internet (Hind, Leach, Lewis and Scott, 2007). In this section, we will summarise key aspects of the evaluation of these two teaching sequences, and then present evaluation evidence for the *Modelling Change* teaching sequence.

Design of the evaluation study

Each of the three teaching sequences was implemented by the three physics, chemistry or biology

teachers who worked in the collaborative group which designed the teaching. A static video camera was used to produce a record of each lesson, and each teacher wore a lapel microphone to provide an audible record of discussions with individual students and small groups. In most cases, a researcher attended the lessons and field notes were made. The video record was analysed to produce a record of the conceptual content of the sequence of lessons, which was compared to the planned sequence of conceptual content. The video record was also analysed to produce a record of the communicative approach used by each teacher, and this was also compared to the planned approach. In this way, the extent to which the enacted teaching compared with the intentions of the design brief could be compared, and addressed in the evaluation.

Students' learning was evaluated using diagnostic questions for conceptual understanding. The questions required students to make a prediction about a phenomenon, and then to explain that phenomenon. Students were therefore able to offer explanations in terms of the model taught through the teaching. Diagnostic questions were used in a pre-test, and the same questions (plus some additional ones to probe more technical content) were used in a post-test. In addition, the same diagnostic questions were used with groups of similar students following the school's usual teaching on the subject. Where pre-test results did not suggest a statistically significant difference between students' understanding prior to teaching, post-test results were used to compare students' understanding following the designed teaching, compared to the understanding of students following the school's usual teaching approach. It is worth emphasising that this aspect of the evaluation used a classic pre- post-test design, rather than analysing individual students' learning through the teaching. This is because our intention was to judge, in the first instance, the extent to which the learning aims of the teaching had been met overall, rather than to judge the relationship of specific teaching activities with learning outcomes.

Each teacher was interviewed before implementing the teaching, and after implementation, to ascertain their reactions to the implementation.

The *Electricity* and *Plant Nutrition* teaching sequences were then implemented by another group

of physics and biology teachers who had not been involved in the design of the teaching. Identical evaluation data were collected and analysed (i.e. pre-test and post-test data, video data and interview data).

Evaluation evidence: Electricity and Plant Nutrition

Data from the diagnostic questions completed by students were analysed as follows. First, students' predictions were coded as correct or not. Their explanations were then categorised into three groups:

- Responses broadly consistent with the scientific model introduced in the teaching ('Consistent');
- Responses that are consistent with the taught model but incomplete in some respect ('Incomplete');
- Other responses ('Other').

These coded responses were averaged across all of the diagnostic questions used.

If data from both the *Electricity* and *Plant Nutrition* teaching sequences are taken together, including all teachers (whether involved or not in the design of the teaching), there are 15 cases where it is possible to compare students' achievement after they followed the designed teaching ('experimental'), with students who followed the school's usual approach ('baseline').

Looking across both sets of data, in 14 of the 15 experimental classes, at least 79.9% of student predictions were correct after following the designed teaching sequences. In addition, students who followed the designed teaching sequences in all 15 cases were significantly more likely to draw upon the conceptual models introduced in teaching, when compared with students in associated baseline groups. Although mean scores for students in classes taught by teachers involved in designing the teaching are higher than those for students taught by other teachers, this difference is not statistically significant.

Interview data from the teachers involved in implementing both the *Electricity* and *Plant Nutrition*

sequences suggested a very positive view of the teaching. Indicative quotations include:

To me it seemed a much better way of going about it and I felt quite excited about the approach. (...) It's not the only way but it's better than what I do now (...) and I just sort of got excited about it.

I don't think in any other lesson that I've done, have I ever gone into using the analogy in that much depth. I might have mentioned it in passing, but not really probed the children for their understanding of the analogy. That's the big difference here and I think it's really valuable.

For a detailed presentation of findings for *Electricity* and *Plant Nutrition*, please see Leach et al. (2006).

Evaluation evidence: Modelling Change

The *Modelling Change* teaching sequence was developed and implemented by three teachers, who

we will refer to as Andy, Lee and Sarah. Pre- and post-test data were collected from students following the *Modelling Change* teaching sequence. As the teaching sequence was intended to revise content that had previously been taught, it was not possible to collect data from students following a comparable teaching sequence in the same school. The test questions required students to make predictions about the conservation of mass during various physical and chemical change processes, and then to explain the prediction using diagrams and words. In the first instance, students' predictions were coded as correct or incorrect. Next, students' explanations were coded as consistent with the taught particle model, partially consistent or inconsistent. In practice, however, most students' explanations were either consistent with the taught model or completely at odds with it and in presenting quantitative data we have conflated all explanations not consistent with the taught model. Table 1 shows data from the pre- and post-test evaluations. Sarah used the *Modelling Change* sequence with two classes.

CASE STUDY	NUMBER OF STUDENTS	PRE-TEST:		POST-TEST:	
		% OF CORRECT PREDICTIONS	% OF CONSISTENT EXPLANATIONS	% OF CONSISTENT PREDICTIONS	% OF CORRECT EXPLANATIONS
ANDY	20	45.0	5.0	83.3	61.7
LEE	28	42.9	2.4	65.4	23.1
SARAH 1	18	16.7	1.9	52.9	23.5
SARAH 2	17	31.4	0.0	60.4	39.6

Table 1: Pre- and post-test data for students following the *Modelling Change* teaching sequence

These data show that students in all 4 classes improved in their ability to make correct predictions about physical and chemical change processes, and to explain them using the taught model, after teaching. However, the data show that in 3 of the 4 groups, the majority of students' explanations were not consistent with the taught model after teaching (i.e. between 76.9% and 60.4%).

Interview data from the teachers who were involved in the design of the *Modelling Change* sequence presents a more equivocal and less positive view than the data from teachers who implemented

the other two teaching sequences. Each of the three teachers worked in a different school. The teachers were invited to join the project because they were known to the research team as enthusiastic and competent chemistry teachers, but none of them had any prior involvement in research.

Interviews with the teachers immediately before the implementation of the *Modelling Change* teaching sequence were mainly positive:

The problem is they'll probably say they've done parts of the lesson and they'd be very right, but what we're

doing is making use of the modelling in a complex situation, which I think is a high level skill. [Andy]

Part of it is down to the quality of the questions – the one I liked was particles in the gas: ‘What is between the gas particles?’ – these are the sorts of things that stick in my mind, that make me think about the sorts of questions I should be asking. [Lee]

When I first started teaching here, I was still doing all these misconception things (laughs) I used to ask them stuff and I used to always be disappointed that they’d give me the right answer (more laughter). [But] I don’t still think that! (...) But when I said it, it was in relation to Year 7 classes. (...) But there was a much bigger level of misconception with Year 9 than there was with the Year 7. [Sarah]

However, both Andy and Lee expressed a desire to have been more involved in actually writing materials, particularly to develop exciting practical activities:

I don’t really feel so far as if I have had much input in the actual planning of the scheme...[Lee]

The teaching was implemented in very different ways by the three teachers. Andy tried to complete every activity in the teaching sequence, rather than selecting activities according to the outcomes of diagnostic questions completed by the students. Lee adapted the sequence to such an extent that it is hard to claim that he followed it. Sarah followed the teaching sequence broadly as intended.

After the teaching had been implemented Andy was quite positive about the teaching sequence:

We were going to look at (...) conservation of mass in the chemical reactions, and physical change (...) but in the end the reality of what we did was very different. (...) What we ended up doing was thoroughly understanding and explaining the particle model of matter, including things that I would never normally teach, like spacing of particles. [Andy]

Well you see, it’s in the discussion. (...) The whole fact that they knew they were going to be asked to give the same explanations (...) they were constantly having to think about the modelling. (...) It’s the difference

between (...) an observation and an explanation. One of the most beneficial things I take forward is that these kids do not understand the particle theory of matter. [Andy]

However, both Lee and Sarah voiced major misgivings about the teaching sequence. Lee’s reservations focused upon the lack of ‘exciting practical work’ in the teaching sequence:

As you saw I’d done other practicals in there that weren’t in the scheme and I think, you know, when it was being planned that part of the time during the planning should have been trying out some practicals that are different from the norm that people will look at and think, ‘Oh!’ [Lee]

It needed stuff in there that was going to be different from the norm. [Lee]

The Cartesian Diver really was – that’s a bit of fun, that. I put that in because they hadn’t done really a practical...[Lee]

There needs to be more student-centred learning in there... I like the demos but they need to be like an intro or a finale and then the students need to be doing something rather than just sat there listening and watching the teacher at the front. I mean Chemistry, science, it’s a practical subject and they need to do practical in there whether it’s a wonderful scheme of work or not. (...) I’m sure there are ways of getting conservation of mass over, particle theory and all that sort of stuff, that they could actually do... [Lee]

Furthermore, Lee did not really talk about *modelling* when describing the aims of the teaching, focusing instead on macroscopic accounts of phenomena:

The main aim of the unit with the demos and the practicals that were in there, the majority of it seemed to concentrate on conservation of mass on the particle side and then using that, for example, with dissolving. (...) They all know, based on what they’ve done, that because nothing has been added, nothing has been taken away, if I leave it on the mass balance the mass will be the same, so I think conservation of mass is the main concept that has been got over in that way. [Lee]

...using the particle theory to explain and understand the conservation of mass, that’s what I think was the

main kind of theme through the unit. (...) You saw the overheads, using the overheads with the particle model on there, explaining those changes. That I think was the key (...) 'It is all there, it is all conserved. It may have escaped or it may have joined, but what we started with we finish with'. [Lee]

Lee felt that his students had achieved a sound conceptual understanding at the end of the teaching:

I think that, in fact I know that, that got over very, very clearly on stuff that we're doing now because they know the answers to all the stuff that I'm doing with them at the moment based on the unit that we did then. (...) I mean, their understanding's excellent...

These comments were made before Lee had seen the summary of his students' post-test data which showed that although 65.4% of the students' predictions were correct, only 23.1% of their explanations were consistent with the taught model. He had, however, looked at the students' post-test responses. This comment reinforces his previous statement that the aim of the teaching was to enable students to make correct predictions about the conservation of mass.

Sarah found the experience of teaching the *Modelling Change* unit stressful, because it did not go according to plan. At the beginning, as noted above, she expected her high-achieving students to find the work unproblematic, but in practice the students found the work extremely challenging. Sarah did not feel that she responded well to the students' difficulties:

I felt embarrassed to be on the video doing what I was doing. (...) That is not a great feeling and it isn't one I've really had before. It was a bit of a shock! [Sarah]

After the teaching, Sarah spoke at length about the focus on modelling:

The aim was to teach the kids how to model using particles. And to get across the main ideas that they tend to get wrong, which would be particles disappearing, growing, shrinking (...) to overcome the misconceptions that they have. (...) I think the solid liquid gas models lead on fairly logically to changes of state. (...) They can see how they go from one to the other. I think the whole chemical change thing is a lot more complicated.

(...) If you are thinking about the particle modelling you've got to do it separately because there are different ideas involved. With physical change (...) you've still got the same number of particles, therefore it has still got the same mass and that is important. (...) With chemical changes you are talking about making new substances and I just think it clouds the water if you try and do them all together. [Sarah]

Furthermore, she talked about her new insights about the teaching approach used in her school:

That throws up things about our scheme of work in that, in Year 9, we always teach chemical reactions before we do materials. I don't know why that is, but we always do and that is a bit daft because (...) if we are doing this chemical change stuff properly then it is too hard if they haven't done the materials stuff. So therefore in the future I would teach them the other way round. [Sarah]

She also indicated surprise at the improvements in her students' performance in the post-test, compared to the pre-test, and said that she had noticed that some students were using the modelling ideas developed in the teaching during subsequent science lessons:

[Referring to the learning data:] It's fairly encouraging isn't it? There are more ups than downs! (...) Certainly Group 1 are much better than I would have thought from how it felt. Definitely, despite all their protestations, they have managed to wedge something in there somehow. [Sarah]

[Referring to subsequent teaching:] I showed them a video and it was something about burning toast and was it going to get heavier or lighter and they actually went, 'Oh it will get lighter cos it will make carbon dioxide.' A couple of them had actually got it, which quite surprised me I have to say. [Sarah]

Due to the difficulties that became apparent during the implementation of the *Modelling Change* teaching sequence, we did not ask a second group of teachers to implement it.

Discussion of the evaluation evidence using the framework

Those who carry out design research hope that the findings from their work will be useful to others

involved in designing teaching. What might other designers take from the evaluation evidence presented in this paper through the use of the framework?

A simplistic conclusion is that the *Electricity* and *Plant Nutrition* teaching sequences 'worked' in that students who followed the sequence were more likely to be able to generate explanations using the models introduced in teaching than their peers who followed their school's usual approach. By contrast, the *Modelling Change* sequence 'failed' in that many students were not able to generate explanations consistent with the content taught model, and furthermore their teachers perceived key weaknesses in the teaching sequence. However, such conclusions are not particularly helpful to other designers who might wish to draw upon findings from the study. It is unlikely that any designer would wish to take any of the three designed teaching sequences and use it without modification. Conclusions about whether the teaching 'worked' or not give no indication as to which parts of the teaching sequence were considered critical to the overall design, and how and why modifications might be made.

In order to enable other designers to draw upon the products of design research, we believe that it is necessary to present evaluation evidence about *the extent to which a worked example (or a part of a worked example) was successful in addressing a design brief (or a part of a design brief)*. This enables more nuanced conclusions to be advanced from evaluation evidence. For example, the worked example did not enable learning demands to be addressed (as demonstrated by Lee's use of several activities in the *Modelling Change* unit focused upon macroscopic explanations for conservation of mass, rather than modelling change processes in terms of particles to account for conservation of mass). This is an issue about the worked example itself, rather than the design brief: the worked example failed to communicate the intentions of the teaching activities in such a way that they were enacted in a manner consistent with their design. In addition, the overall formulation of the worked example (i.e. the wording of student activities, teacher notes) did not enable teachers to use the designed activities to achieve the intentions in the design brief (for example, Andy's interpretation of the *Modelling Change* unit as requiring him to complete all activities, rather than using activities according to

the outcomes of formative assessment). Again, this is an issue where the worked example, rather than the design brief itself, was found to be wanting.

However, the design brief did not give sufficient attention to some aspect of the local environment (for example, the reaction of Sarah's students to being presented with formative assessment questions on content that they had already been taught, without the opportunity for revision, or Lee's inclusion of additional practical work into the *Modelling Change* unit on the grounds that it did not contain enough opportunities for student practical work). Although the evaluation study for *Modelling Change* did not suggest this problem, it is obviously possible for a design brief to omit key learning demands, which results in students' learning being in some respect less adequate than intended. A failure to address the role of bonding in the worked example would have been along these lines.

So, what conclusions can be drawn from our evaluation of the *Modelling Change* teaching sequence? A first conclusion is that the worked example failed to address the design brief in that the evaluation evidence about students' ability to use the taught model suggests that between 38% and 77% of students' explanations after teaching did not draw upon the taught model. In addition, the worked example did not succeed in motivating two of the three teachers involved in the study. For these reasons, we would not advocate the use of the *Modelling Change* teaching sequence by other teachers without significant modification. However, there is no evidence to suggest that our initial analysis of learning demands requires modification; rather, it appears that there are weaknesses in the worked example and the design brief itself.

The design brief required teachers to make formative assessments of their students' ability to use a previously-taught particulate model of matter to explain a range of change processes, and to shape their subsequent use of the *Modelling Change* teaching sequence according to the outcomes of that assessment. The worked example did not enable at least one of the three teachers to do this. As previously mentioned, *Modelling Change* was the first of the three teaching sequences to be designed. Based upon this finding, the design briefs for both the *Plant*

Nutrition and *Electricity* teaching sequences required lessons to be developed which placed more modest requirements upon teachers to select activities from a range of possible choices. In each case, the worked examples that were developed specified the precise content of each lesson in some detail.

A further conclusion from the evaluation of the *Modelling Change* teaching sequence is that the worked example failed to enable one of the teachers (Lee) to use the sequence to develop his students' ability to use a model to generate explanations, a key aspect of the design brief. Rather, Lee appeared to view the aim of the teaching sequence as developing his students' understanding of a macroscopic explanation of the conservation of mass in change processes. Future worked examples might address this limitation by providing more explicit teacher guidance.

So far, the conclusions that are being drawn relate to the different ways in which the *Modelling Change* worked example failed to address aspects of its design brief, because it did not enable the teachers to carry out the teaching in a manner consistent with the design brief. Given that the teaching was not conducted in a manner consistent with the design brief, there is little purpose in evaluating, at a fine grain size, pupils' learning in response to various aspects of the teaching intervention. There is also evidence to suggest that the design brief itself is flawed. For example, the data about students' use of a simple particle model to construct explanations of change phenomena before teaching (between 1.9% and 5% of explanations) suggests that it was inappropriate to design a teaching sequence to revise previously taught content. A more appropriate aim would have been to introduce students to a model, and support them in learning to use the model, working systematically from relatively simple change processes (mixing, phase change) to more complex changes where new substances are formed. Although the design brief for *Modelling Change* included reference to modelling a range of change processes, it did not justify the selection of particular pedagogic strategies (using an analogy, using empirical evidence, etc.) to address teaching purposes and learning demands, on the grounds that it was assumed that students already had a working understanding of the simple particle model used to explain physical and chemical change.

These conclusions, all at a large grain size, show how the evaluation study illuminated weaknesses in both the worked example, and the design brief itself. If a design is unsuccessful in several respects at a large grain size, these weaknesses have to be addressed in order to address aspects of detail at a finer grain size. The *Electricity* and *Plant Nutrition* worked examples were more successful than the *Modelling Change* sequence, in that students' understanding after teaching was considerably better, and both students and teachers responded positively to the teaching. How might this be explained?

In the first instance, we draw attention to the difference between the design brief for *Modelling Change*, and those for *Electricity* and *Plant Nutrition*. The design briefs for the more successful units made appropriate assumptions about students' starting points. They also provided a clear rationale about the pedagogic strategies that were to be used in the teaching in order to address staging, supporting internalisation and handing-over, at a fine grain size.

This can be illustrated with reference to part of the *Electricity* teaching sequence. Based on an analysis of learning demands, the design brief required the teaching to open up for students the inadequacy of linear sequential models of simple circuits (electricity originates in a source, passes through the circuit, and is used in some way in a device such as a lamp in the circuit). The design brief then required the teaching to introduce an analogy in order to make plausible to students a simple physics model of electric circuits as systems, replacing students' undifferentiated notion of 'electricity' with 'charge' and 'energy'. The worked example that was developed began with an activity in which students had to predict what would happen when a simple series circuit with very long wires was connected (the BIG circuit; see Scott et al. 2006). As expected, many students predicted that there would be a significant time delay between connecting a wire of the circuit to the power source, and the lamp lighting. When the circuit was connected, students were surprised that there was no discernable time delay, opening up a problem to be explained. An analogy was then introduced to explain the behaviour of the circuit, and to bridge between the simple physics model and

the phenomenon. Given the evaluation evidence, we conclude that this part of the worked example (i.e. the BIG circuit, followed by the use of the analogy to introduce a simple physics model and bridge from the model to the phenomenon) was successful in addressing the design brief. However, in subsequent work the precise details of the analogy that was used have been changed, based upon further evaluation evidence (Scott, 2005).

Conclusion

In this paper, we have justified in terms of a social constructivist perspective on learning science in formal settings why science teaching sequences need to include staging, supporting internalisation and handing-over. These phases of a teaching sequence are at a large grain size, and we have described two design tools (learning demand and communicative approach) which inform, at a fine grain size, decisions about the conceptual aims of teaching and the pedagogical approach to be used. We introduced, and differentiated between, design briefs and worked examples of teaching, and showed how evaluation

evidence can give insights about the quality of each. We showed how differentiating between the *design brief*, and a *worked example* to address a design brief, enables evaluation decisions to be made about whether a particular teaching sequence is successful in addressing its design intentions, or rather whether the design intentions themselves need modification. This was exemplified by illustrating how the worked examples used in the *Electricity* and *Plant Nutrition* teaching sequences addressed design flaws in the *Modelling Change* design brief. This enabled teachers using the physics and biology sequences to teach them in such a way that students' learning outcomes were significantly better than the learning outcomes of their peers being taught by the school's usual approach. We made the point that worked examples have to enable teachers to use teaching sequences in a manner broadly consistent with their design intentions, before it is possible to evaluate a design brief and worked example at a finer grain size.

We hope that other designers may find this framework useful in designing and evaluating science teaching, and in communicating about the design process.

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APPENDIX 1: Illustrative 'Thought Experiment' used in the Modelling Change teaching sequence

Daniel, Inderjit and Michael are weighing some metal petrol cans. They are using a balance beam. The balance beam is level. This means that 'A' and 'B' have the same mass.

Next, they use a bicycle pump to pump some extra air into can B.

Daniel says: The extra air in B will make it **lighter**, so it will go **upwards**.

Inderjit says: The extra air in B will make it **heavier**, so it will go **downwards**.

Michael says: The extra air will make **no difference** to the mass of the cans, so the balance beam will **stay level**.

Discuss this thought experiment with your partner.

Which of the boys do you think is right?

What would you say to convince the other two boys that your answer is correct? Give as much detail as you can!

APPENDIX 2: Illustrative Diagnostic question used in the post-test for the Modelling Change teaching sequence

Name:

Modelling change

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Thought Experiment 1: Weighing Air

Daniel, Inderjit and Michael are weighing some metal petrol cans. They are using a balance beam.

The balance beam is level.

This means that 'A' and 'B' have the same mass.

Next, they use a bicycle pump to pump some extra air into can B.

Daniel says: The extra air in B will make it **lighter**, so it will go **upwards**.

Inderjit says: The extra air in B will make it **heavier**, so it will go **downwards**.

Michael says: The extra air will make **no difference** to the mass of the cans, so the balance beam will **stay level**.

Discuss this thought experiment with your partner.

Which of the boys do you think is right?

What would you say to convince the other two boys that your answer is correct? Give as much detail as you can!