Cases on Research-Based Teaching Methods in Science Education

Eugene de Silva
Virginia Research Institute, USA & MRAS - Walters State Community College, USA

A volume in the Advances in Educational Technologies and Instructional Design (AETID) Book Series

Information Science REFERENCE
An Imprint of IGI Global

Managing Director: Lindsay Johnston
Production Editor: Christina Henning
Development Editor: Erin O'Dea
Acquisitions Editor: Kayla Wolfe
Typesetter: Michael Brehm
Cover Design: Jason Mull

Published in the United States of America by
Information Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Cases on research-based teaching methods in science education / Eugene de Silva, editor.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4666-6375-6 (hardcover) -- ISBN 978-1-4666-6376-3 (ebook) -- ISBN 978-1-4666-6378-7 (print & perpetual access) 1. Science--Study and teaching--United States. 2. Technology--Study and teaching--United States. 3. Science--Study and teaching--Great Britain. 4. Technology--Study and teaching--Great Britain. 5. Effective teaching. I. De Silva, Eugene, editor.
Q183.3.A1C387 2015
507.1--dc23
2014021075

This book is published in the IGI Global book series Advances in Educational Technologies and Instructional Design (AETID) (ISSN: 2326-8905; eISSN: 2326-8913)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

Chapter 6
Developing a Research-Informed Teaching Module for Learning about Electrical Circuits at Lower Secondary School Level:
Supporting Personal Learning about Science and the Nature of Science

Keith S Taber
University of Cambridge, UK

Neil Mercer
University of Cambridge, UK

Kenneth Ruthven
University of Cambridge, UK

Fran Riga
University of Cambridge, UK

Christine Howe
University of Cambridge, UK

Riikka Hofmann
University of Cambridge, UK

Stefanie Luthman
University of Cambridge, UK

EXECUTIVE SUMMARY

This chapter discusses the design and development of a teaching module on electrical circuits for lower secondary students (11-14 year olds) studying in the context of

DOI: 10.4018/978-1-4666-6375-6.ch006

the English National Curriculum. The module was developed as part of a project: "Effecting Principled Improvement in STEM Education" (epiSTEMe). The electricity module was designed according to general principles adopted across epiSTEMe, drawing upon research and recommendations of good practice offered in curriculum guidance and the advice offered by classroom practitioners who tested out activities in their own classrooms. The module design was informed by the constructivist perspective that each individual has to construct their own personal knowledge and so rejects notions that teaching can be understood as transfer of knowledge from a teacher or text to learners. However, the version of constructivism adopted acknowledged the central importance of social mediation of learning, both in terms of the role of a more experienced other (such as a teacher) in channeling and scaffolding the learning of students and the potential for peer mediation of learning through dialogue that requires learners to engage with enquiry processes and interrogate and critique their own understanding.

BACKGROUND

Introduction

This chapter describes the development of a research-informed teaching module on electrical circuits for early secondary level (in particular aimed at 11-12 year olds) developed as part of the project 'Effecting Principled Improvement in STEM Education' (epiSTEMe). The principles informing the design of the module will be discussed, and the way those principles were applied in module development will be explored. Three levels of context for appreciating module development will be provided relating to issues of (i) research into student thinking and learning in the topic, (ii) the context of the epiSTEMe project more generally, and (iii) the wider curriculum context in which the work took place.

Student Thinking and Learning about Electrical Circuits

There is an extensive body of research exploring student learning and thinking in various science topics (Duit, 2009; Taber, 2009), including electricity and electric circuits (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Shipstone et al., 1988). Learning difficulties relating to the topic of electrical circuits are well established, and these are found across the secondary age range. A common problem concerns students not appreciating how current will be constant around a series circuit. A naive view would be that this could be countered by demonstration: simply showing learners a series circuit and measuring the current at various points.

A somewhat more informed view – informed by research into science learning (considered below) – might suggest that something more than this is needed: to first help learners make explicit their intuitive ideas about what would happen in the circuit, and then counter these by providing the evidence that their intuitions do not match what actually happens. This might be expected to lead to cognitive dissonance, and so motivate learning to make sense of the discrepant observations (Driver & Oldham, 1986).

This approach is commonly recommended because human beings generally manage to perceive the world as fitting expectations (finding matches between what is sensed and existing implicit knowledge elements such that perception is biased to fit existing cognitive structures) - what is sometimes known as confirmation bias (Nickerson, 1998). Driver noted how students put in open-ended discovery learning situations with minimal 'scaffolding' from teaching tended to fail to spot the patterns that it was hoped they would find salient and seldom 'discover' the scientific principles hoped for (Driver, 1983). Much more recent work has reinforced how rarely students take away from school science practical work the ideas such activities are intended to motivate or illustrate (Abrahams, 2011).

One pedagogic approach intended to address this issue is known as P-O-E, which stands for Predict-Observe-Explain (White & Gunstone, 1992). The principal assumption drawn upon here is that by first having students make predictions they would then be primed to extract the desired 'figure' from the 'ground' of sensory data - to borrow terms from the Gestalt psychologists (Koffka, 1967) - and also have some investment in observing a particular pattern or outcome. Where expectations are confounded, the potential cognitive dissonance (Cooper, 2007) is harnessed by asking students to explain what they have observed – thus reinforcing the outcome and requiring the learner to actively seek to make sense of the unexpected observations. This is considered important because research in science education suggests that learners commonly revert to alternative conceptions supported by their intuitions despite teaching events, once those events cease to be recent (Taber, 2003).

Interestingly, some research suggests that even employing the P-O-E strategy may be insufficient to overcome students' expectations about what goes on in electric circuits. A study showed that when a class of 14-year olds was asked to predict how current would vary round a simple series circuit most of the students predicted current would diminish around the circuit as previous studies had suggested (Gauld, 1986, 1989). This prediction can be tested by ammeters, or by using lamp brightness as an indicator (as long as similar lamps are used at different points in a circuit). After seeing the demonstration students accepted current did not change around the circuit, seeming to have changed their ideas about current in circuits. However when the same students were interviewed three months later many had reverted to their initial thinking – that current diminishes around a series circuit.

These students often remembered the demonstration, but now thought what they had seen fitted their initial predictions. So even when learners' prior thinking is made explicit, AND they are shown their predictions are wrong, AND they accept they were wrong and seem to change their minds, this may not be sufficient to bring about long-term conceptual change.

Human cognition has inherent drives for coherence and consistency (Jolliffe & Baron-Cohen, 1999; Parkin, 1993). It would seem that in Gauld's study, the observation of a confounding outcome was sufficient to lead students to accept a new way of thinking that matches the unexpected outcome, but without sufficient reinforcement of the new learning (Vertes, 2004) many students worked towards coherence by modifying their memory of the observations, rather than their preferred mental models of electrical current flow around circuits.

Electricity as a Challenging Topic

It is perhaps not surprising that electrical circuits is a topic which many students find difficult (Shipstone et al., 1988). Whilst students can observe and manipulate simple circuits, and indeed many students seem to enjoy this type of practical work, the ideas involved are challenging. Electrical circuits are explained in terms of abstract ideas, in particular current and potential difference (p.d. or 'voltage') that link to the concepts of charge and energy respectively. Energy is acknowledged as a highly abstract topic – for example by Nobel laureate physicist Richard Feynman (1965) - which students commonly struggle with (Brook & Driver, 1984; Solomon, 1992; Watts, 1983). Current as a flow of charge can potentially be visualised, but to apply this idea to circuits students have to shift from considering the observable phenomena at the macroscopic 'bench' scale, to think about a process occurring at a submicroscopic scale. At this scale the apparently solid metal wires students observe are understood as a fixed lattice arrangement of atomic cores bound by electrical forces to a fluid-like (Buddle, Niedderer, Scott, & Leach, 2002) ensemble of delocalised electrons (see Figure 1). However, this model is not usually explicitly taught until much later in secondary education.

It has long been recognised that part of the challenge of school science learning relates to how learners are asked to cope with presentations at several 'levels' at once (Johnstone, 1982, 1991). In particular, students are often presented with two distinct re-descriptions or re-conceptualisations of phenomena they can observe, framed in terms of the technical symbolic language, theoretical concepts, and explanatory models used in science. In many topics students not only have to learn how an observable phenomena is categorised and conceptualised in formal terms (say a candle flame in terms of categories of chemical reaction and combustion)

Figure 1. Conceptualising electrical circuits at two levels (Adapted from Taber, 2013)

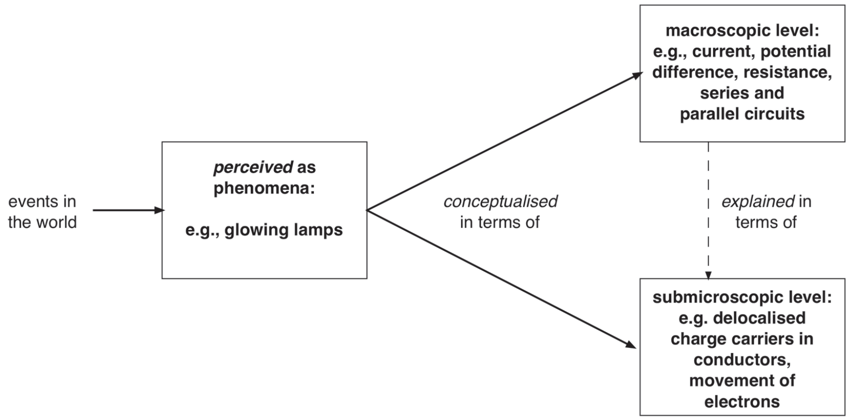
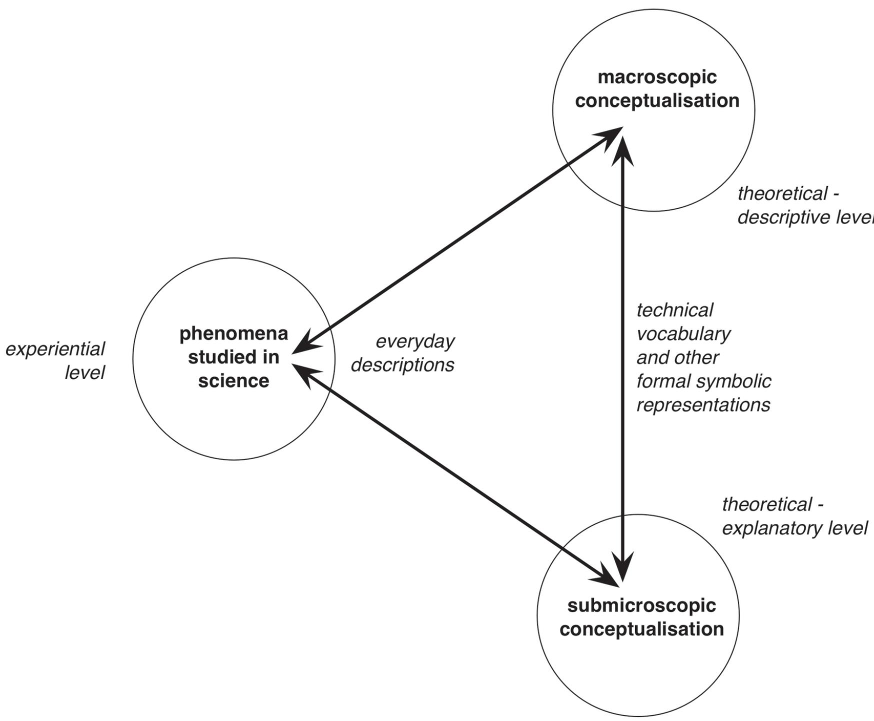


Figure 2. Science teaching as moving between different levels or domains (Adapted from Taber, 2013)



but also how scientists explain the phenomena in terms of models of the structure of matter at submicroscopic scales (see Figure 2).

Circuit Diagrams

A key part of the challenge of learning about electrical circuits is the use of a scientific formalism to represent circuits - circuit diagrams. To the experienced physicist or science teacher a circuit diagram has probably come to be perceived as quite like a circuit: it has the important affordances of both offering 1:1 correspondence between components and their symbols, and also clearly reflecting the topology of the circuit, and so how different components are connected.

However, learners faced with circuit diagrams may find they less obviously reflect actual circuits, and can find it very difficult to build circuits from circuit diagrams. Students have to both identify specific components from different symbols, and appreciate how the formalism of straight lines and sharp corners can represent the key aspects of the arrangement of various leads - inevitably taking up myriad configurations on the bench, but seldom appearing linear.

Common Alternative Conceptions

Although current passing through wires is often made more accessible to students through the use of teaching models making analogies (discussed further below) with, for example, fluid flow through pipes, this offers limited explanatory power by itself. Secondary students commonly commence formal study of the topic of electricity with a vague notion of ‘electricity’ from everyday discourse, which is not differentiated between current, potential difference, energy and power (Arnold & Millar, 1987). Students commonly initially make sense of circuits in terms of intuitive ideas that lead to mental models that have been labelled as ‘unipolar’ (something comes from one side of the cell or battery to the component) or ‘clashing current’ (something different comes from each side of the cell or battery and meets at the component).

Generally then a major shift is needed to persuade learners to consider that something, charge in the form of a current, is flowing all around the circuit. However, this shift does not lead to a mental model of circuits that can support desired learning unless current as a flow of charge is clearly distinguished from current as a means of transferring energy. For one thing, current is conserved around circuits, despite work being done in lamps and other components. Moreover, the charge that is flowing does not really go anywhere (although in a direct current circuit individual electrons do slowly drift around the circuit) – in the sense that the electrons in the wires are simply replaced by other, entirely equivalent, electrons. The only structural difference between the current carrying wire, and the same wire when it is not carrying current, is that in the former case there is a very slight drift superimposed on the otherwise random patterns of electron movements in the metal. (Indeed in a.c. circuits, such as that used in house lighting, there is not even a net drift – and typically electrons may only shift a fraction of a millimetre before the direction of flow switches). The speed of electron drift in a simple circuit is extremely slow from a macroscopic perspective. Even in a physically small circuit it might take quite a few minutes for a particular electron to move through a distance equivalent to that from the cell terminals to a lamp: yet the circuit seems to work instantaneously. Students do not have to wait several minutes for lamps to glow or ammeters to register current.

Circuits as Systems

The effect of current flow therefore can only be understood by coordinating ideas about current with something else – energy or electrical potential. The circuit can be understood as a device for transferring energy and the mobile charges that make up the current are in effect energy carriers. A circuit needs to be understood in terms of this process (i.e. systematically), but as Chi has reported, learners tend to conceptualise scientific processes in terms of substances, and it is then difficult to reassign the concept to a very different 'ontological tree' (Chi, 2008; Chi, Slotta, & de Leeuw, 1994). Of course this is not a tendency of school students in particular – the history of science offers many examples adopted by respected scientists – not just electrical fluid as used by Benjamin Franklin among others, but caloric, phlogiston, the ether, vital forces, etc. - of substances or pseudo-substances once mooted as elements of scientific explanations but now discredited.

Measurements of potential difference (i.e. 'voltages' in common parlance) are indicators of the amount of energy being transferred in sections of the circuit. Where students commonly expect current to diminish around the circuit, the scientific account suggests they should instead be paying attention to the voltmeter readings between different points around the circuit as this relates to where work is being done in different components. In a series circuit with two dissimilar lamps, apparent phenomenologically as glowing with different degrees of brightness, the same current flow will pass through both (being determined by the total p.d. across the circuit and its total resistance) but the p.d. across the two lamps will differ.

An electric circuit is therefore a system, and in a sense it is an emergent system, as the different specific components, and their configuration, need to be specified to understand what is going on at any point. Studies on student understanding of systems suggest school age learners often have limited basis for understanding systems and emergent phenomena (Wilensky & Resnick, 1999).

Taking these considerations together, it is perhaps less surprising that secondary age students tend to (i) focus their thinking about circuits on current (something they can visualise); thus (ii) think primarily in terms of a substance-like entity (rather than thinking in terms of process); (iii) consider the parts of a circuit sequentially attempting to understand each point locally (rather than as one part of an interacting system); and (iv) conceptualise the circuit in terms of current moving from a source (the battery) and being 'used up' around the circuit. This alternative conceptual framework is more accessible than the scientific alternative.

Given the very real barriers to effective learning about circuit concepts, and in particular the abstract understanding needed to make good sense of circuits, it might be questioned whether this is a suitable topic for teaching students at the start of secondary education – perhaps instead electronic circuits should only be taught at this age as part of technology classes so that students become familiar with components and their affordances, to provide a context for theoretical learning later in the school. However, in the English curriculum context discussed below (as many others) teaching and learning about circuits is prescribed for lower secondary level science.

Challenges of Teaching Electrical Concepts through Simple Circuit Work

Research suggests that although many students enjoy practical work in school science, and some certainly develop competence in manipulative work (meeting educational objectives in the sensori-motor domain), such activities are often less successful in engaging students in using their observations to support conceptual learning. Many school practicals are meant to illustrate scientific principles (Millar, 2004): but in science the link from observation to theory is often not straight-forward (Kuhn, 1996; Lakatos, 1999), and expecting students to draw the 'right' conclusions without careful scaffolding is often unrealistic (Abrahams & Millar, 2008). Moreover, whereas research scientists practise and refine techniques they use on a regular basis, school students are generally operating with relatively unfamiliar apparatus and techniques. This adds to the excitement of lessons, but undermines learning in two ways.

Firstly scientific apparatus often needs nursing to 'work' as intended. Polanyi (1962) stressed how scientific work depends upon 'tacit' knowledge that scientists develop over time: implicit knowledge of how to get particular set-ups to work that relies on close familiarity with that kit and laboratory environment. In principle, scientific papers provide all the details for others to undertake the replications that are part of science - but in practice new experimental set-ups can sometimes only be transferred between research groups when scientists visit other labs so that the scientist with the specialist experience can model the processes to others (Collins, 2010).

Whilst the type of apparatus involved in school practical work in electricity is routine and far from the forefront of research, it is notorious for being problematic. Practical work can be spoiled for example by corroded switches and contacts; intermittent faults due to unseen breaks in insulated leads; old cells with high internal resistance (so the measured terminal p.d. drops significantly as soon as an external load is applied); lamps with partly evaporated filaments having very different power ratings to other nominally identical lamps; and poorly calibrated meters. These difficulties can only be avoided when technical support is available to carefully check all kit before each lesson - a time-intensive process - and the teacher or support staff are able to fault-find during student work.

A second problem concerns the limits of human working memory (Baddeley, 2003). People can only mentipulate a limited about of material at any one time. School practical work generally involves relatively novel aspects for learners (reducing the potential for 'chunking' to use working memory more effectively). Following instructions, collecting and manipulating apparatus, and recording observations may 'load' students' working memories in full. This will leave limited, if any, capacity for the kinds of reflection on what is being experienced in relation to (often recently introduced) concepts that is needed for what Abrahams (2011) refers to as 'minds-on', rather than just 'hands-on', practical work.

SETTING THE STAGE

Electrical Circuits in the English Lower Secondary Curriculum

The present chapter describes the process of developing a research-informed teaching module to support learners in developing a scientifically appropriate understanding of simple electrical circuits. The work reported here derives from the English context, where electricity is a major topic in the lower secondary school. At the time of developing the module as part of the epiSTEMe project the English National Curriculum for Science for 11-14 year old students had recently been revised (QCA, 2007). The new curriculum document might be considered 'content-lite' compared to the previous version of the curriculum (DfEE/QCA, 1999), in part as a deliberate attempt (a) to counter concerns about how in the previous curriculum excessive prescription of content was limiting depth of treatment and restricting the teacher's flexibility and creativity in meeting needs of particular students (Hacker & Rowe, 1997; Jenkins, 2000; Kind & Taber, 2005); and (b) to balance prescription of subject content with wider objectives relating to skill development and understanding the nature of science (QCA, 2005).

The physics content of the revised science curriculum for teaching across three years of study (for 11-14 year olds) was reduced to "The study of science should include energy, electricity and forces: (a) energy can be transferred usefully, stored, or dissipated, but cannot be created or destroyed; (b) forces are interactions between objects and can affect their shape; and motion; (c) electric current in circuits can produce a variety of effects" (QCA, 2007. p.210). The notes provided in the curriculum to explain the scope of the material to be taught about electricity (point c above) was limited to "Circuits: This includes current and voltage in series and parallel circuits" (QCA, 2007. p.210).

This provided limited guidance for teachers and a sharp change of approach. The previous much denser curriculum document had been supplemented by non-statutory schemes of work (QCA, 2000), and an extensive 'national strategy' for teaching science built around a comprehensive framework document suggesting how progression in understanding key concepts should be supported across the three years of the lower secondary phase (Key Stage 3 National Strategy, 2002).

Teaching about 'How Science Works' as Part of the Science Curriculum

Part of the rationale for the new curriculum was to increase the emphasis within the secondary curriculum on the nature of science, or 'how science works' in the terminology used in the curriculum documents. The importance of teaching about the outcomes of science within a wider context has been recognised in many national contexts for some decades. In the 1980s there was an 'STS' movement that sought to prioritise teaching about 'science and technology in society' (McConnell, 1982). There has also been a widespread movement to teach more about the nature of science itself - in particular through informing school curricula with scholarship in the history and philosophy of science (Duschl, 2000; Hodson, 2009; Matthews, 1994).

When the UK government decided to introduce a national curriculum into English schools (Statutory Instrument, 1989), the original proposals for the science curriculum included an attainment target focused on the nature of science. However, later simplification of the proposals led to this aspect becoming largely implicit - leading to it having limited effect on practice (Donnelly, 2001). Several attempts were later made to address this concern through tweaks to the curriculum, guidance documentation, and the assessment regime (Taber, 2008).

The 2007 revision of the curriculum was more substantial, reducing specification of science content to be taught to brief topic descriptions such as those above, and setting this content as just one of several aspects of the curriculum: so 'range and content' (as it was headed) followed what was referred to as 'key concepts' and 'key processes' (QCA, 2007). "Key concepts that underpin the study of science and how science works" (p.208) included scientific thinking, applications and implications of science, cultural understanding and collaboration. 'Key processes' related to practical and enquiry skills, critical understanding of evidence, and communication (p.209). Under the heading of 'scientific thinking' students were expected to use "us[e] scientific ideas and models to explain phenomena and develop... them creatively to generate and test theories" and "critically analys[e] and evaluat[e] evidence from observations and experiments" (p.208).

The TISME Initiative and the epiSTEMe Project

The epiSTEMe project was part of an overarching *Targeted Initiative on Science and Mathematics Education* (TISME). TISME is a programme of research funded by the UK's Economic and Social Research Council in partnership with the Gatsby Charitable Foundation, The Institute of Physics and the Association of Science Education. The aim of the initiative was to find new ways to encourage children and young people to greater participation, engagement, achievement and understanding of Science and Mathematics. The initiative funded a number of projects including one based at the University of Cambridge: *Effecting Principled Improvement in STEM Education* (epiSTEMe). EpiSTEMe was concerned with student engagement and learning in early secondary school physical science and mathematics.

The epiSTEMe project set out to develop classroom activities and supporting materials that drew upon research-based approaches in four lower school science and mathematics topics: probability and proportionality in mathematics and forces and electric circuits in science. Our aspiration however, was not simply to support the teaching of four topics, but to demonstrate how research-based pedagogy could be built into school teaching schemes. It was hoped that if schools used and saw the value of our modules these would provide experience in a particular teaching approach and offer models of effective classroom activities. We looked to frame classroom tasks that could help build students' abilities to think as mathematicians and scientists and support key conceptual advances in a topic. In particular, tasks were designed to trigger critical examination of common alternative conceptions. Lessons were planned around carefully crafted problem situations intended to appeal to shared student experiences and interests. As the intention of epiSTEMe was to adopt research-informed pedagogy, suitable existing classroom-tested activities were incorporated into the modules alongside newly designed activities.

A distinctive feature of the *epiSTEMe* approach is its use of dialogue – in small student groups and the whole class – to elicit and examine differing points of view on problem situations (Howe et al., 2007; Kleine-Staarman & Mercer, 2010). As it was recognised that students (and teachers) need to develop skills in working through such approaches, an introductory module was developed to build teacher and student understanding of the value of talk and dialogue in supporting subject thinking and learning, and to help teachers develops rules and processes to underpin effective small-group and whole-class discussion. As a result, two topic modules in each of science and mathematics were designed to stimulate and capitalise on talk and dialogue, based on the assumption that ground-rules and good working habits had been established through the introductory module.

The epiSTEMe team worked closely with teachers from several schools over an 18-month period to develop, trial and refine the intervention. The development process drew on the expertise of teachers and researchers, as well as on a synthesis of relevant research literature (Ruthven et al., 2010) and analysis of evidence from classroom trialling. Its aim was to generate resources for developing teachers and teaching students, as well as to improve understanding of teaching and learning processes in school science and mathematics.

Teachers from partner schools enrolled in the project attended project days with the university team to discuss the aims of the project, to explore the pedagogic approach, to critique (and sometimes try out) draft activities and to make suggestions for modifications or additional activities drawing on their own teaching repertoires. In particular the classroom practitioners were able to offer advice on how the constraints of their real teaching contexts should be considered in planning teaching and learning activities. Sometimes teachers were video-recorded trying out activities with their own classes to allow later review at a project day. Through this process, module materials were refined sufficiently to be suitable for testing in schools that had not been part of the development process.

CASE DESCRIPTION

Principles Adopted in Developing the Electricity Module

The module on electric circuits was informed by the general principles adopted in epiSTEMe, combined with specific considerations particular to the topic. A feature shared with the other topic modules was orchestration of lessons to permit shifts between student group work and teacher-led full classroom discussion; and which moved between eliciting and examining students' own thinking, and considering the canonical curriculum accounts reflecting scientific concepts and models. This is the type of approach discussed by Mortimer and Scott (2003) in their exploration of classroom science teaching. This is considered further below.

The perspective informing the development of the module was personal constructivism, in the sense of psychological or pedagogic constructivism (Glasersfeld, 1989; Sjøberg, 2010; Taber, 2009), which suggests that each person has to interpret their experiences to construct their own understanding of the world. The corollary of this principle is that all learning is contingent upon the interpretative frameworks available to a learner and so the teacher cannot assume that teaching will be understood as intended. Sometimes personal constructivism is presented as being in opposition to social constructivism or constructionism, but the version of constructivism adopted here fully acknowledged that human learning normally takes place in a social context, and that culture provides affordances and constraints on learning (Kleine-Staarman & Mercer, 2010; Scott, 1998). School learning is often highly contingent not only upon the student's prior learning, but also on features of the classroom context (Finkelstein, 2005): such as curriculum, teaching approach, teacher language, teaching models, and in particular learning activities and the opportunities for engagement with ideas these provide.

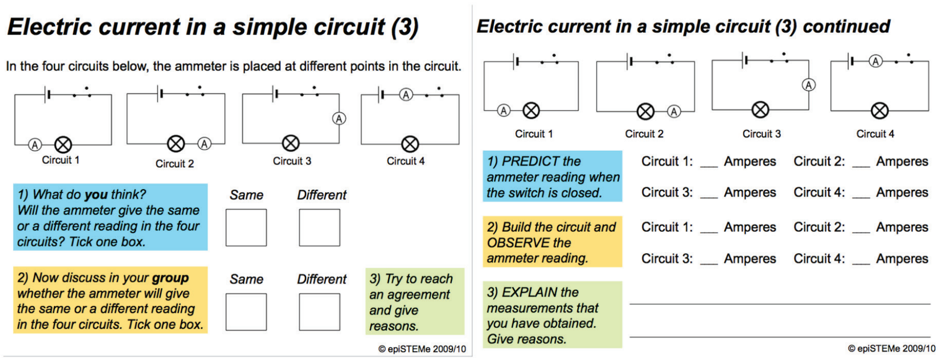
The module included an extended series of group practical activities of building and examining simple circuits. In selecting electricity as a project topic it would have been possible to have focused on building circuits with different transducers (lamps, buzzers, light dependent resistors, light emitting diodes etc) in response to problems that could have been contextualised in everyday situations. So, for example, students could have been asked to build a circuit that turned on a light if it was dark when someone (who could not see the light switch) whistled. This would have motivated problem-solving through everyday relevance (and would have matched the kind of approach used extensively in the other epiSTEMe topic modules). Such an approach could have treated circuit components as 'black boxes' and been based on how technological solutions are met by using logic gates and various transducers in different combinations.

However, as suggested above, the key problem for science educators in a curriculum context that expects learners to understand basic circuit principles is how to help learners to acquire a scientific model of current in circuits that distinguishes the flow of charge itself from the energy being transferred through the circuit. It was decided therefore to focus on these more fundamental abstract aspects of circuits rather than their technological applications. Given the problems, described above, that lower secondary students often experience in making sense of scientific models of circuits, there might be a case for arguing that theoretical understanding could be deferred to upper secondary level, and that it is more appropriate to provide experience of practical uses in the lower secondary school: but since the prescribed curriculum was set out in terms of the physical principles, these were addressed.

Minds-On Practical Work

As suggested above, there are significant challenges in expecting students, especially those in the lower secondary school relatively unfamiliar with circuit work, to

Figure 3. Predict-observe-explain was used to motivate dialogue within groups



make the desired links between observations made when constructing circuits and the concepts they are expected to learn. In particular, these concepts will often be contrary to the mental models students develop from their intuitive ways of making sense of electrical circuits.

The core of the module was a sequence of practical activities organised around building simple series and parallel circuits. Despite the potential difficulties associated with practical work it was considered important to include ‘hands-on’ work to motivate students to see a need for modelling what was going on in circuits by presenting actual phenomena to be explained.

In order to ensure the work was also minds-on this was undertaken within a dialogic frame at two levels. Firstly, the circuit investigations were to be undertaken within groups where (a) students had been taught about effective group work in the epiSTEMe introductory module, and (b) the P-O-E technique was adopted so that circuit building would be undertaken with a view to testing particular ideas about what was going on in circuits (e.g. see Figure 3).

Secondly, the teaching and learning activities were designed to shift between group work and classroom-led discussion where the teacher was asked to work with students’ ideas and explore their adequacy in relation to the empirical observations. It was also recommended that (given the potential for equipment failures to lead to anomalous results) the teacher should reinforce student findings by using either a large demonstration version of the circuits students were building, or projected computer simulations of the circuits, to ensure that the scientifically ‘correct’ observations were being discussed and recorded by students.

This central core to the module involved learners in a succession of similar activities as they built a sequence of circuits allowing comparisons to be made between different arrangements of circuit components. We were aware in designing the module that different classes would progress through the material at different rates, and that teachers saw the limited number of lessons they could commit to any particular topic as a major constraint. We therefore included some optional material, and wrote modules that allowed differentiation by giving teachers flexibility to choose to omit some activities for some groups of students.

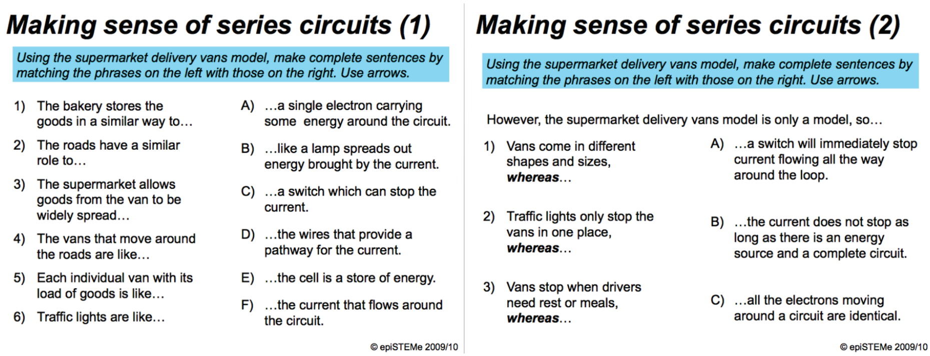
The epiSTEMe electricity module allows learners to work their way through a series of closely related practical exercises to help them build up a conceptual understanding of phenomena - that is it offers an opportunity to experience a much more authentic form of scientific enquiry than a series of discrete stand alone practicals each related to a distinct scientific idea. This more authentic approach also helps counter the problems referred to above of working with unfamiliar kit which tends to lead to a major part of both time on task and working memory capacity being given over to manipulation, leaving less resource for mentipulation of the ideas the practical work is meant to link to.

Building upon Existing Good Practice

The epiSTEMe project, then, sought to build upon, and develop design principles around, existing research and demonstrated good practice. Within the electricity module this was enacted in two ways. The common use of models and analogies in teaching this topic was developed and made a key focus of the module (see below). In addition it was decided by the research team that rather than just writing new activities, it was important to include existing research-informed teaching resources developed by other researchers. In particular we draw upon two existing sources. One of these is the UK's Institute of Physics' 'Supporting Physics Teaching 11-14' materials (Whitehouse, 2002). The other is guidance materials published as part of a government funded 'National Strategy' (The National Strategies Secondary, 2008). These in turn drew upon activities designed as part of a teaching scheme (Hind, Leach, Lewis, & Scott, not dated) developed at the University of Leeds during a funded project (the *Teaching and Learning Research Project* funded by the UK Economic and Social Research Council).

So for example, one of the activities included in the epiSTEMe module was 'the big circuit' - a teacher-led activity asking students about what would happen to a lamp when a switch is closed in a circuit that is set up around the full perimeter of the room for dramatic effect. The teacher elicits student thinking about the circuit, and in particular the time it might take for a lamp some considerable distance from a switch or battery to light. The activity is designed around two conceptual tools referred to as 'learning demand' and the 'communicative approach' (Ruthven, Laborde, Leach, & Tiberghien, 2009). Learning demand (Leach & Scott, 2002) concerns analysing the 'gap' between students' current thinking and the canonical

Figure 4. Questions highlighting the mapping of an analogy to electric circuits



account presented in the curriculum - that is, it is a constructivist model stressing the importance of diagnostic assessment in classroom teaching (Taber, 2014). The communicative approach (Mortimer & Scott, 2003) refers to the kind of dialogic teaching referred to earlier where the teacher moves between exploring different ideas suggested by learners and presenting and advocating the scientific account set out as target knowledge in the curriculum.

The Use of Teaching Analogies and Models

Another feature of existing good practice built into the epiSTEMe module was the use of teaching analogies for thinking about what is going on in circuits. In the Big Circuit activity, for example, as presented in the original Leeds teaching scheme, a 'teaching story' is introduced to compare the circuit with an everyday situation that would be accessible to learners: the delivery of bread from bakeries to keep supermarkets stocked by fleets of delivery vans (Hind, Leach, Lewis, & Scott, Not dated). A key feature of this analogy is that although it is the vans flowing around the distribution network, the number of vans is conserved as they act as carriers of something else - loaves of bread (see Figure 4). This is analogous to how electrons in circuits act as 'carriers of energy' allowing energy to be transferred from the store in the battery to the lamp (or other transducer) by a current that is constant around the circuit (as current reflects the amount of charge flowing at a point, not the energy associated with it).

The use of teaching analogies of this kind is ubiquitous in science teaching across a wide range of topics (Harrison & Coll, 2008; Harrison & Treagust, 2006). The principle here is simple enough: teaching is about making the unfamiliar familiar, and one way we can do this (especially where there is not the option of directly demonstrating a teaching point) is to make comparisons with what is already familiar. Teachers use explicit analogies as well as metaphors and similes to help learners anchor new ideas within existing propositional knowledge, and so to ensure teaching is perceived meaningfully and more likely to lead to learning (Ausubel, 2000). So it might be said that the nucleus is the control centre for a cell, that enzymes fits into substrates like a lock and key, and so forth.

Such devices are very common in teaching, although it is recognised that there are potential problems. Students at secondary level often display a relatively limited appreciation of the epistemological role and nature of models and analogies (Treagust, Chittleborough, & Mamiala, 2002) - for example treating comparisons more 'literally' or realistically than is intended. In the case of analogies, students may transfer inappropriate attributes from the analogue to the target (Nakiboglu & Taber, 2013; Taber, 2001) unless teaching is clear about the positive and negative aspects of the analogy (Gentner, 1983). Despite these limitations, previous work with trainee teachers teaching about the nature of ideas and evidence in science had suggested that there was considerable potential to support learning about electricity by working with analogies, models and creative writing (Taber, de Trafford, & Quail, 2006).

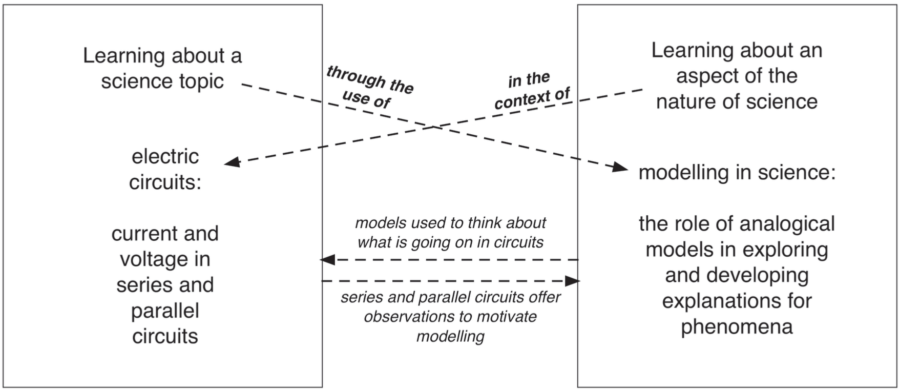
MAKING MODELS AND ANALOGIES A CENTRAL FEATURE OF THE MODULE

The incorporation of teaching models and analogies in a module on electric circuits was not in itself novel, however the epiSTEMe module went beyond this. The module was designed to be in the spirit of the recent curriculum changes (discussed above) in that it foregrounded learning about the role of models and analogies in science alongside the learning of the specific topic of electric circuits. That is, the inclusion of models and analogies was not intended just to support learning about circuits, but also to support learning about a key feature of the nature of science (or 'how science works') that was highlighted in the new curriculum (QCA, 2007).

The intention then was to build synergy into the design (see Figure 5). The use of teaching models and analogies would help learners make the unfamiliar world of electrons and potential difference meaningful by comparison with familiar situations and experiences. However, the topic of electric circuits would also provide an authentic context for exploring how scientists use such devices as thinking tools in their work - for example in making predictions to test through empirical investigation.

This aim also had the advantage of offering a response to the minority of students (sometimes including some of those who already have a relatively strong concep-

Figure 5. Synergy between learning about scientific ideas, and learning about the nature of science



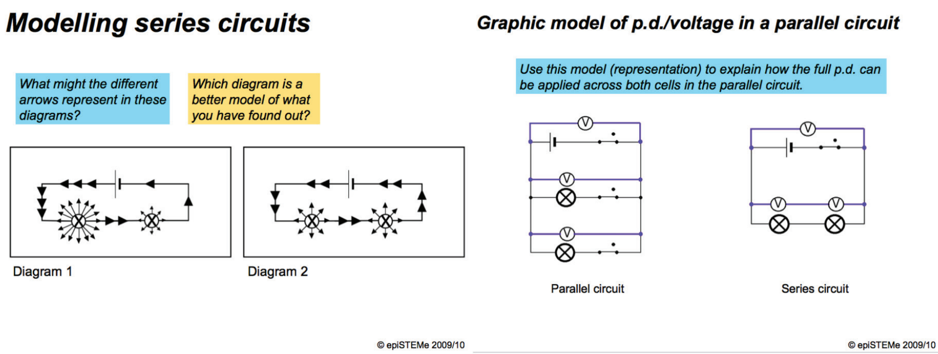
tual understanding of a topic) who consider the use of teaching analogies and some other models as 'silly' and feel the teacher is either being condescending in using them or intends them only for the low attaining students in the class.

THE USE OF MULTIPLE MODELS

An important feature of this approach was the use of multiple models, in keeping with the principle that learning abstract scientific ideas is supported by the use of multiple representations (Tsui & Treagust, 2009; Tytler, Prain, Hubber, & Waldrip, 2013). Simply offering one model that generally 'worked' might have supported learning about electric circuits but without teaching about the role of models, and with the danger of inappropriate transfer of associations of the model, or the expectation that the model would always 'work' (apply) even though models and analogies generally have limited ranges of application.

Teachers were encouraged to elicit learners' own suggestions and develop those, but built into the teaching materials were three models that student were explicitly asked to consider and seek to apply. One of these was a version of the supermarkets/bread van model discussed above. A second was based on a physical model students could try in class using a loop of rope that was held in the hands of a series of people around the 'circuit' to represent current flow. The third model was a role-play (Dorion, 2009) where students take on the role of electrons moving packets of energy from a source (battery) to another circuit component (lamp).

Figure 6. The module included opportunities to work with representations to model aspects of circuit phenomena



There is now an increasing awareness in science teaching that learning is often supported by both multi-modal teaching (Jewitt, Kress, Ogborn, & Tsatsarelis, 2001), and through asking students to find alternative ways of representing the same information (Tytler et al., 2013). The first analogical model was taught primarily through diagrams: the other two involved embodied learning - through students interacting with a physical model of current in a circuit, and playing a part in a physical simulation of current.

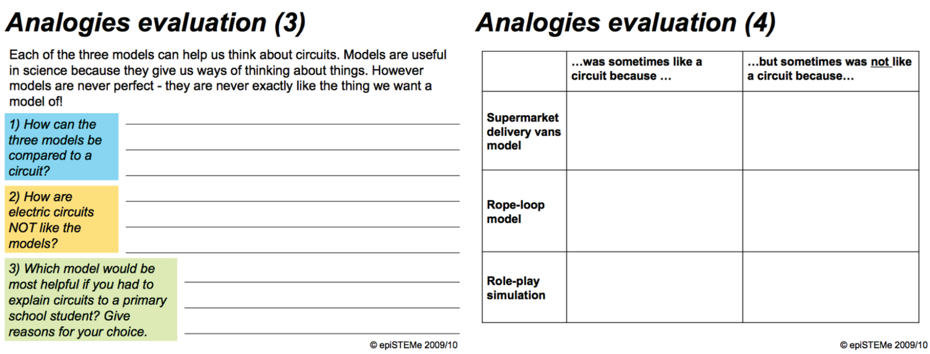
Offering three models motivated genuine questions about the extent to which the different models 'worked' in supporting thinking about different aspects of the actual circuits students could build, and how predictions informed by thinking about the different models were or were not supported by observations of actual circuits. In addition to the analogical models explored through the module, explicit opportunities were built into the module to consider the affordances of different kinds of representations of circuit phenomena (e.g., see Figure 6).

Teaching about Models and Analogies in Science

The intention that analogies and models should take a central role in the module was reflected in the inclusion of explicit teaching about this theme early in the module. Slides to introduce the use of analogy in science were included in the teaching materials provided, along with related activities. These included asking learners to suggest their own analogies - an activity that had been successfully used in an earlier project (Taber, 2007).

The three different analogical models built into the module were introduced and explored through teacher led discussion. The students were then asked to work

Figure 7. Students were asked to explicitly evaluate the models they had used throughout the module


Analogies evaluation (3)

Each of the three models can help us think about circuits. Models are useful in science because they give us ways of thinking about things. However models are never perfect - they are never exactly like the thing we want a model of!

1) How can the three models be compared to a circuit?

2) How are electric circuits NOT like the models?

3) Which model would be most helpful if you had to explain circuits to a primary school student? Give reasons for your choice.

© epiSTEMe 2009/10

Analogies evaluation (4)

	...was sometimes like a circuit because ...	...but sometimes was not like a circuit because...
Supermarket delivery vans model		
Rope-loop model		
Role-play simulation		

© epiSTEMe 2009/10

with the models when undertaking the 'P-O-E' based investigations of a sequence of circuits. During the teacher-led classroom discussions the teachers were asked to explore and work with student thinking about both the circuits themselves and the models. Later in the module students were asked to critique and evaluate the three analogical models they had used through the unit (e.g., see Figure 7).

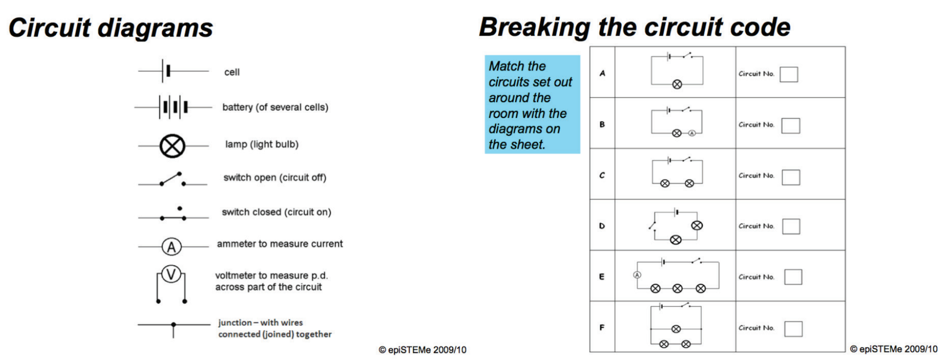
Extensive Use of Circuit Diagrams

As suggested above, circuit diagrams offer an additional challenge for students in circuit work. This was a concern for some of the teachers we worked with, as they rightly recognised how presenting formal circuit diagrams to students added to the cognitive demand of the work. On the advice of the teachers we included hybrid diagrams (showing pictorial representations of components in circuits) in the earliest activities of the module. However it was felt to be important to ask students to engage with formal circuit diagrams for much of the work as this is a core form of representation used in science that allows ready tracing of the key topological features of circuits (in particular where current splits in parallel branches).

Moreover, in a module with a strong focus on models and modelling in science, circuit diagrams offered an example of a commonly used representational model. It was also considered that, as with using the practical apparatus, asking students to undertake an extended sequence of activities using the representations would support developing familiarity to the point where this ceased to make a major demand upon student working memory.

We incorporated an initial diagnostic activity into the module asking students to match circuits from the two types of diagrams, thus giving teachers an opportunity

Figure 8. Building familiarity with circuit diagrams is considered an important prerequisite to working effectively with such diagrams in circuit building



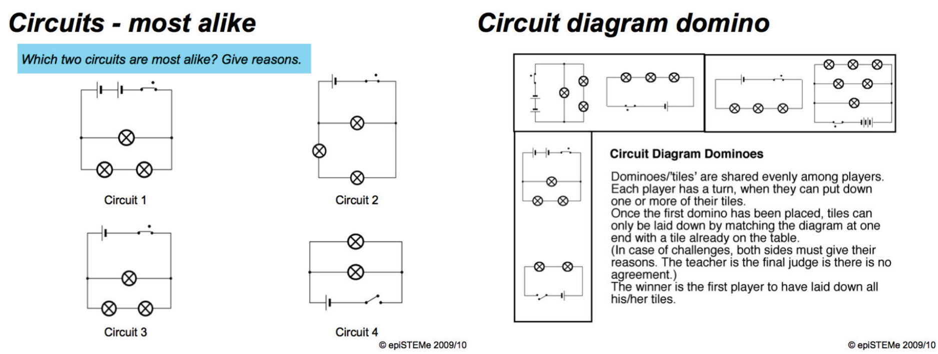
to see whether students could readily cope with the representations, for example perhaps based on earlier primary school work on electricity. Early in the module students were introduced to a small selection of circuit symbols to be used in the lessons, along the lines that "circuit diagrams are a special kind of model that is useful to *represent* circuits in science. Circuit symbols are like a special (graphical/diagrammatic) language or code". The students then undertook an activity on 'breaking the circuit code' (see Figure 8) that asked groups to visit 6 different circuits set up at stations around the teaching room and work out which circuit matched each of six circuit diagrams on their worksheet.

This introductory activity preceded the group practical work where students were asked to think about circuits represented as diagrams in terms of the three analogical models, and then to build the circuits represented. At the end of module, one of the review activities provided was a game of circuit dominoes - which required students to recognise where differently drawn circuit diagrams represented substantially the same circuit (see Figure 9). This was provided with different levels of complexity, to allow differentiation in the challenge of the task.

The epiSTEMe Module

After various drafts, and piloting by teachers in our partner schools, a version of the module was produced that the project team felt was ready for making available to teachers more widely. The module materials comprise a series of slides for teacher presentation to support discussion; a workbook for students; teachers' notes (see Figure 10) and technician notes. These are all available to any educator or researcher who contacts the authors.

Figure 9. Review activities reinforced working with, and thinking about, the circuit diagram formalism



Although we recognised that teachers would need to organise material according to their school timetable structures (as length of lessons - classroom periods - vary between schools) and to meet the needs of particular teaching groups, we were encouraged by teacher partners to present the activities within nominal coherent lessons (see Figure 10). We expected teachers to retain the sequence of the module, but not to feel bound by the suggestions for how much material was to be included in a particular lesson.

CURRENT CHALLENGES

One comment received in feedback on the electricity module was that the work on building the different circuits was time-consuming and involved students undertaking a number of similar activities (that is, building a sequence of circuits embedded within group-work structured around P-O-E). The implication was that school science should not be repetitive - even though arguably much professional science is precisely of this nature. This may reflect an apparent obsession within the school inspection system in the UK on 'pace': that students should be seen to be making progression in moving forward in their learning. Some teachers felt that school inspectors (or senior staff from their own schools conducting lesson observations) would expect to see obvious progression between clearly discrete activities - each with its own closure within the lesson. Teachers in England feel they are expected to demonstrate new learning at the end of each lesson, even though educational research shows that substantive conceptual change is a slow process that requires integration across sequences of learning activities (Vosniadou, 2008). Clearly there

Figure 10. Teaching and learning activities were organised into possible lessons that could each be undertaken in classroom period of about an hour

Overview of the Teaching Notes

is a danger here of teachers focusing on achievable short-term objectives to the detriment of longer-term aims.

This can be a real concern if teachers are worried about spending extended periods developing ideas because they feel they should be seen to be moving on to something that is clearly (to students, and any visiting inspectors) 'different'.

Common criticisms of the English science curriculum have been the lack of depth which limits engagement with concepts - something that is of particular importance to the most gifted learners in science (Taber, 2010) - and the tendency for teachers to limit practical work to that considered to be clearly linked to formal assessment (Hacker & Rowe, 1997).

A serious concern then is that making our materials available unconditionally, without for example requiring attendance at related professional development sessions, risks our activities being used without being informed by the research-based design principles. Many teachers practise a form of professional bricolage, acquiring teaching materials to be 'mixed-and-matched' and adapted to fit existing teaching habits. Yet teaching with the epiSTEMe materials may not reflect the epiSTEMe approach unless teachers adopt something of the philosophy behind the project and incorporate the pedagogy we have put together rather than just use the materials. A key feature is the dialogic aspect, which requires both that teachers prepare students for effective group work, and that teachers orchestrate the shifts between inviting and exploring different views, and presenting the case for the scientific account.

Within the electricity module itself, our specific additional concerns are that teachers will not give students sufficient time to work carefully through the sequence of activities as intended, or may fail to maintain the exploration of the analogical models through the different circuit contexts that allows learners to appreciate how models are used and evaluated as thinking tools. In particular, unless teachers insist that learners take time to work through the P-O-E activities as instructed, shortcuts will be taken in building circuits before carefully thinking through what is expected to happen. The limited observational work we were able to carry out in the epiSTEMe project with teachers who had not been involved in the development process suggests these are real concerns, at least in the UK context.

SOLUTIONS AND RECOMMENDATIONS

Our experience in piloting the materials with partner project teachers was that students certainly demonstrated learning gains in relation to understanding electrical circuits through the module. Pre- and post-tests were developed using assessment questions based on existing assessment materials for this topic to ensure content validity, as we intended to undertake a randomised field trial of the modules by comparing students in classes of teachers having attended two days of teacher development and using the materials, with students in (as far as possible) matched schools working with teachers teaching according to their usual schemes and approaches. (These teachers of 'control' classes were offered teacher development and access to all the materials at the end of this process. The trial has now been completed, although analysis of data is not yet complete.)

The epiSTEMe electricity module integrated teaching and learning about a science topic, electric circuits, with teaching and learning about a key feature of the nature of science, the role of models and modelling. Any learning gains in relation to this key curriculum aim would be in addition to the learning that took place about circuits themselves. As it would have been unfair to test students on this aspect of learning in classes where teachers were not following the epiSTEMe module, we did not collect data about this during the field trials.

The epiSTEMe project reinforced the possibility of designing teaching modules in science and mathematics according to what are now well-established pedagogic principles. The project also reminded us of the barriers to working in partnership with schools in such projects - personnel changes and constraints due to other school priorities limited the continuity of the wider development team and restricted the opportunities for effective piloting of materials. Two schools that worked with us throughout the development process have since worked towards embedding the pedagogy exemplified through epiSTEMe more widely into departmental teaching - but have to date succeeded to different degrees.

Our observations of classes using epiSTEMe materials taught by teachers who had attended our teacher development days reminded us of the difficulties of bringing about changes in teacher behaviour in their classrooms. Expecting teachers to shift towards more dialogic teaching approaches without extensive support and opportunities for feedback and review may be overly optimistic. Whilst this should remain an important aim, it is clear many teachers find it difficult to make substantial changes from familiar classroom approaches and this might reinforce the importance of research-informed *initial* teacher education programmes in setting up effective pedagogic habits from the start of a teaching career.

The materials from epiSTEMe are now available, and the authors would welcome approaches from those who wish to either critique them to inform their work in research-based instructional design, or even to test them out in teaching in their own local educational contexts. The electricity module might be of particular interest to those exploring how to embed learning about nature of science objectives into teaching of mainstream science topics. There has been debate about the best ways to teach nature of science objectives in relation to science ‘content’ objectives (Hodson, 2009), and the adoption of the electricity module design would benefit from careful examination in this regard. We would welcome evaluation of the module in diverse classroom contexts, especially where it is possible to (a) explore classroom processes (e.g. the nature of student group work; the extent of dialogicity in teaching); and (b) to simultaneously investigate learning gains across both the domains of physics subject knowledge (electric circuits) and the nature of science (the role of models and modelling in science).

ACKNOWLEDGMENT

The research reported here was only made possible by the support of teachers from partner schools, and funding from the Economic and Social Research Council through grant RES-179-25-0003: 'Effecting Principled Improvement in STEM Education: Student Engagement and Learning in Early Secondary-School Physical Science and Mathematics'.

REFERENCES

Abrahams, I. (2011). *Practical work in school science: A minds-on approach*. London: Continuum.

Abrahams, I., & Millar, R. (2008). Does Practical Work Really Work? A study of the effectiveness of practical work as a teaching and learning method in school science. *International Journal of Science Education*, *30*(14), 1945–1969. doi:10.1080/09500690701749305

Arnold, M., & Millar, R. (1987). Being constructive: An alternative approach to the teaching of introductory ideas in electricity. *International Journal of Science Education*, *9*(5), 553–563. doi:10.1080/0950069870090505

Ausubel, D. P. (2000). *The Acquisition and Retention of Knowledge: a cognitive view*. Dordrecht, The Netherlands: Kluwer Academic Publishers. doi:10.1007/978-94-015-9454-7

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829-839.

Brook, A., & Driver, R. (1984). *Aspects of Secondary Students' Understanding of Energy: Full Report*. Leeds, UK: Centre for Studies in Science and Mathematics Education, University of Leeds.

Budde, M., Niedderer, H., Scott, P., & Leach, J. (2002). 'Electronium': A quantum atomic teaching model. *Physics Education*, *37*(3), 197–203. doi:10.1088/0031-9120/37/3/303

Chi, M. T. H. (2008). Three types of conceptual change: belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 61–82). New York: Routledge.

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes; a theory of conceptual change for learning science concepts. *Learning and Instruction*, *4*(1), 27–43. doi:10.1016/0959-4752(94)90017-5

Collins, H. (2010). *Tacit and Explicit Knowledge*. Chicago: The University of Chicago Press. doi:10.7208/chicago/9780226113821.001.0001

Cooper, J. (2007). *Cognitive Dissonance: Fifty years of a classic theory*. London: Sage.

DfEE/QCA. (1999). Science: The National Curriculum for England, key stages 1-4. London: Department for Education and Employment/Qualifications and Curriculum Authority.

Donnelly, J. (2001). Contested terrain or unified project? 'The nature of science' in the National Curriculum for England and Wales. *International Journal of Science Education*, *23*(2), 181–195. doi:10.1080/09500690120412

Dorion, K. R. (2009). Science through Drama: A multiple case exploration of the characteristics of drama activities used in secondary science lessons. *International Journal of Science Education*, *31*(16), 2247–2270. doi:10.1080/09500690802712699

Driver, R. (1983). *The Pupil as Scientist?* Milton Keynes, UK: Open University Press.

Driver, R., & Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education*, *13*(1), 105–122. doi:10.1080/03057268608559933

Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making Sense of Secondary Science: research into children's ideas*. London: Routledge.

Duit, R. (2009). *Bibliography - Students' and Teachers' Conceptions and Science Education*. Retrieved from http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html

Duschl, R. A. (2000). Making the nature of science explicit. In R. Millar, J. Leach, & J. Osborne (Eds.), *Improving Science Education: the contribution of research* (pp. 187–206). Buckingham: Open University Press.

Feynman, R. (1965). *The Character of Physical Law*. Cambridge, MA: MIT Press.

Gauld, C. (1986). Models, meters and memory. *Research in Science Education*, *16*(1), 49–54. doi:10.1007/BF02356817

Gauld, C. (1989). A study of pupils' responses to empirical evidence. In R. Millar (Ed.), *Doing Science: images of science in science education* (pp. 62–82). London: The Falmer Press.

Gentner, D. (1983). Structure-Mapping: A Theoretical Framework for Analogy. *Cognitive Science*, *7*(2), 155–170. doi:10.1207/s15516709cog0702_3

Hacker, R. G., & Rowe, M. J. (1997). The impact of a National Curriculum development on teaching and learning behaviours. *International Journal of Science Education*, *19*(9), 997–1004. doi:10.1080/0950069970190901

Harrison, A. G., & Coll, R. K. (Eds.). (2008). *Using analogies in middle and secondary science classrooms*. Thousand Oaks, CA: Corwin Press.

Harrison, A. G., & Treagust, D. F. (2006). Teaching and learning with analogies: friend or foe? In P. J. Aubusson, A. G. Harrison & S. M. Ritchie (Eds.), Metaphor and Analogy in Science Education (pp. 11-24). Dordecht, The Netherlands: Springer.

Hind, A., Leach, J., Lewis, J., & Scott, P. (n.d.). *Teaching for understanding: Electic circuits: A teahcing scheme developed from research evdience on students' learning about electric circuits*. Academic Press.

Hodson, D. (2009). *Teaching and learning about science: Language, theories, methods, history, traditions and values*. Rotterdam, The Netherlands: Sense Publishers.

Howe, C., Tolmie, A., Thurston, A., Topping, K., Christie, D., & Livingston, K. et al. (2007). Group work in elementary science: Towards organisational principles for supporting pupil learning. *Learning and Instruction*, *17*(5), 549–563. doi:10.1016/j.learninstruc.2007.09.004

Instrument, S. (1989). The Education (National Curriculum) (Attainment Targets and Programmes of Study in Science). *Order*, 1989.

Jenkins, E. W. (2000). The impact of the national curriculum on secondary school science teaching in England and Wales. *International Journal of Science Education*, *22*(3), 325–336. doi:10.1080/095006900289903

Jewitt, C., Kress, G., Ogborn, J., & Tsatsarelis, C. (2001). Exploring Learning Through Visual, Actional and Linguistic Communication: The multimodal environment of a science classroom. *Educational Review*, *53*(1), 5–18. doi:10.1080/00131910123753

Johnstone, A. H. (1982). Macro- and microchemsitry. [Notes and correspondence]. *The School Science Review*, *64*(227), 377–379.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*(2), 75–83. doi:10.1111/j.1365-2729.1991.tb00230.x

Jolliffe, T., & Baron-Cohen, S. (1999). A test of central coherence theory: linguistic processing in high-functioning adults with autism or Asperger syndrome: is local coherence impaired? *Cognition*, *71*(2), 149–185. doi:10.1016/S0010-0277(99)00022-0 PMID:10444907

Key Stage 3 National Strategy. (2002). *Framework for teaching science: years 7, 8 and 9*. London: Department for Education and Skills.

Kind, V., & Taber, K. S. (2005). Science: Teaching School Subjects 11-19. London: RoutledgeFalmer.

Kleine-Staarman, J., & Mercer, N. (2010). The guided construction of knowledge: Talk between teachers and students. In K. Littleton, C. Wood & J. K. Kleine-Staarman (Eds.), International Handbook of Research of Psychology in Education (pp. 75-104). Bingley, UK: Emerald.

Koffka, K. (1967). Principles of Gestalt Psychology. In J. A. Dyal (Ed.), *Readings in Psychology: Understanding human behavior* (2nd ed., pp. 9–13). New York: McGraw-Hill Book Company.

Kuhn, T. S. (1996). *The Structure of Scientific Revolutions* (3rd ed.). Chicago: University of Chicago. doi:10.7208/chicago/9780226458106.001.0001

Lakatos, I. (1999). Lectures on Scientific Method. In M. Motterlini (Ed.), *For and Against Method* (pp. 19–109). Chicago: University of Chicago Press. doi:10.7208/chicago/9780226467030.001.0001

Leach, J., & Scott, P. (2002). Designing and evaluating science teaching sequences: An approach drawing upon the concept of learning demand and a social constructivist perspective on learning. *Studies in Science Education*, *38*(1), 115–142. doi:10.1080/03057260208560189

Matthews, M. R. (1994). *Science Teaching: The role of history and philosophy of science*. London: Routledge.

McConnell, M. C. (1982). Teaching about Science, Technology and Society at the secondary school level in the United States. An educational dilemma for the 1980s. *Studies in Science Education*, *9*(1), 1–32. doi:10.1080/03057268208559893

Millar, R. (2004, 3-4 June 2004). *The role of practical work in the teaching and learning of science*. Paper presented at the High School Science Laboratories: Role and Vision, National Academy of Sciences. Washington, DC.

Mortimer, E. F., & Scott, P. H. (2003). *Meaning Making in Secondary Science Classrooms*. Maidenhead, UK: Open University Press.

Nickerson, R. S. (1998). Confirmation bias: A ubiquitous phenomenon in many guises. *Review of General Psychology*, *2*(2), 175–220. doi:10.1037/1089-2680.2.2.175

Parkin, A. J. (1993). *Memory: Phenomena, experiment and theory*. Hove, UK: Psychology Press.

Polanyi, M. (1962). Personal knowledge: Towards a post-critical philosophy (Corrected version ed.). Chicago: University of Chicago Press.

QCA. (2000). *Key stage 3 schemes of work*. Qualification and Curriculum Authority.

QCA. (2005). *Science: 2004/5 annual report on curriculum and assessment*. London: Qualifications and Curriculum Authority.

QCA. (2007). *Science: Programme of study for key stage 3 and attainment targets*. London: Qualifications and Curriculum Authority.

Renström, L., Andersson, B., & Marton, F. (1990). Students' conceptions of matter. *Journal of Educational Psychology*, *82*(3), 555–569. doi:10.1037/0022-0663.82.3.555

Ruthven, K., Howe, C., Mercer, N., Taber, K. S., Luthman, S., Hofmann, R., & Riga, F. (2010). Effecting Principled Improvement in STEM Education: Research-based pedagogical development for student engagement and learning in early secondary-school physical science and mathematics. In M. Joubert & P. Andrews (Eds.), *British Congress of Mathematics Education* (pp. 191-198). British Society for Research into Learning Mathematics.

Ruthven, K., Laborde, C., Leach, J., & Tiberghien, A. (2009). Design Tools in Didactical Research: Instrumenting the Epistemological and Cognitive Aspects of the Design of Teaching Sequences. *Educational Researcher*, *38*(5), 329–342. doi:10.3102/0013189X09338513

Shipstone‡, D. M., Rhöneck, C., Jung, W., Kärrqvist, C., Dupin, J.-J., Johsua, S., & Licht, P. (1988, July). A study of students' understanding of electricity in five European countries. *International Journal of Science Education*, *10*(3), 303–316. doi:10.1080/0950069880100306

Solomon, J. (1992). *Getting to Know about Energy - in School and Society*. London: Falmer Press.

Nakiboğlu, C., & Taber, K. S. (2013). The atom as a tiny solar system: Turkish high school students' understanding of the atom in relation to a common teaching analogy. In G. Tsaparlis, & H. Sevian (Eds.), *Concepts of Matter in Science Education* (pp. 169–198). Dordrecht, The Netherlands: Springer. doi:10.1007/978-94-007-5914-5_8

Taber, K. S. (2001). When the analogy breaks down: Modelling the atom on the solar system. *Physics Education*, *36*(3), 222–226. doi:10.1088/0031-9120/36/3/308

Taber, K. S. (2003). Lost without trace or not brought to mind? - a case study of remembering and forgetting of college science. *Chemistry Education: Research and Practice*, *4*(3), 249–277.

Taber, K. S. (2007). *Enriching School Science for the Gifted Learner*. London: Gatsby Science Enhancement Programme.

Taber, K. S. (2008). Towards a curricular model of the nature of science. *Science & Education*, *17*(2-3), 179–218. doi:10.1007/s11191-006-9056-4

Taber, K. S. (Ed.). (2009). *Progressing Science Education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer. doi:10.1007/978-90-481-2431-2

Taber, K. S. (2010). Challenging gifted learners: General principles for science educators; and exemplification in the context of teaching chemistry. *Science Education International*, *21*(1), 5–30.

Taber, K. S. (2013). Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14*(2), 156–168. doi:10.1039/c3rp00012e

Taber, K. S. (2014). *Student Thinking and Learning in Science: Perspectives on the Nature and Development of Learners' Ideas*. New York: *Routledge.*

Taber, K. S., de Trafford, T., & Quail, T. (2006). Conceptual resources for constructing the concepts of electricity: The role of models, analogies and imagination. *Physics Education*, *41*(155-160).

The National Strategies Secondary. (2008). *Explaining how electric circuits work: Science teaching unit*. Department for Children, Schools and Families.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education*, *24*(4), 357–368. doi:10.1080/09500690110066485

Tsui, C.-Y., & Treagust, D. (2010). Evaluating Secondary Students' Scientific Reasoning in Genetics Using a Two-Tier Diagnostic Instrument. *International Journal of Science Education*, *32*(8), 1073–1098. doi:10.1080/09500690902951429

Tytler, R., Prain, V., Hubber, P., & Waldrip, B. G. (Eds.). (2013). *Constructing Representations to Learn in Science*. Rotterdam: Sense Publishers. doi:10.1007/978-94-6209-203-7

Vertes, R. P. (2004). Memory Consolidation in Sleep. *Neuron*, *44*(1), 135–148. doi:10.1016/j.neuron.2004.08.034 PMID:15450166

Vosniadou, S. (Ed.). (2008). *International Handbook of Research on Conceptual Change*. London: Routledge.

Watts, M. (1983). Some alternative views of energy. *Physics Education*, *18*(5), 213–217. doi:10.1088/0031-9120/18/5/307

White, R. T., & Gunstone, R. F. (1992). *Probing Understanding*. London: Falmer Press.

Whitehouse, M. (2002). Supporting Physics Teaching (11-14). *Physics Education*, *37*(5), 363.

Wilensky, U., & Resnick, M. (1999). Thinking in Levels: A Dynamic Systems Approach to Making Sense of the World. *Journal of Science Education and Technology*, *8*(1), 3–19. doi:10.1023/A:1009421303064

KEY TERMS AND DEFINITIONS

Constructivist Perspectives on Learning: Constructivist perspectives on learning consider that knowledge is not 'out there', waiting to be found, but is constructed by people as they make sense of the world, and that there are constraints on this process (for example, limitations characteristic of human perception and cognition). Personal constructivism sees the key processes of learning occurring within the minds (and so the brains) of individual learners, whereas social constructivists put more emphasis on the ways culture and social interaction shape learning and the development of understanding. Whichever emphasis is adopted, it is recognised that what is learned is highly contingent on a range of factors that include elements of the learner's existing conceptual structure (e.g. prior knowledge and beliefs) and how these interact with specific features of teaching and the social context of learning. In the context of the reported project one example would be how the electrical circuits module was designed to give opportunities for the elicitation of common alternative conceptions (such as the idea that current values must change around a simple series circuit) and their consideration in relation to empirical evidence collected by students.

Design of STEM Teaching Modules: Teaching of formal curriculum is often organised into sections (often referred to as modules or units) based around a particular topic or concept area - such as electrical circuits. STEM teaching modules are these units of planned teaching in the relatively cognate subject areas of science, technology, engineering and mathematics. The design of STEM teaching modules in the reported project included considerations about the selection and sequencing of content, but also considerations about how features of effective and research-informed pedagogy are adopted when planning the teaching and learning activities and supporting curriculum and assessment materials. For example, the adoption of a constructivist perspective on learning informs the way teaching is designed to acknowledge and respond to students' existing ideas, and a commitment to dialogic teaching informs how canonical ideas are introduced and developed in the classroom and related to students' existing ideas.

Dialogic Teaching: Teaching is understood as behaviour which is intended to bring about learning. Dialogic teaching is that in which both teachers and learners make substantial and significant contributions to classroom talk. The teacher encourages learners to participate actively and so enables them to articulate, reflect upon and modify their own understanding, while also providing them with clear guidance, feedback and authoritative accounts of relevant knowledge when appropriate. It normally involves both teacher-led, whole-class sessions and group-based activities where learners can learn collaboratively. An important basis for dialogic teaching is that both the teacher and the learners appreciate the potential value of talk for learning, and of how that potential can best be realised.

Learning about Electrical Circuits: 'Electrical circuits' is here understood as a focus of the topic of 'electricity' which is set out as part of the lower secondary school curriculum in England. In particular, in the context of the reported project, this concerns learning about how electrical current flowing in a circuit relates to the configuration of the circuit (e.g. the number of resistive components and how they are arranged).

Learning Science: Learning is understood in this chapter as a change in the potential for behaviour. In the context of the reported project this could mean that after learning a student is able to offer an explanation of what electrical current is that they could not have offered before learning, or that after learning a student could offer reasons why using analogies to model circuits reflects scientific practice that they would not have been able to suggest prior to learning.

School Science Practical Work: The term ‘practical work’ within school science is usually intended to refer to laboratory or field work carried out by students. Such activity is often described by students as ‘experiments’ although much school practical work has involved practising of laboratory techniques, or carrying out procedures to demonstrate accepted (rather than to test conjectured) ideas. Practical work includes enquiry (or inquiry) work where students undertake authentic investigations as well as more routine activities. Sometimes such activities as the secondary analysis of existing data sets have been considered to fall under the heading ‘practical work’ although this does not involve students themselves in the ‘practical’ activities of collecting data through observations and measurements. Arguably, it is useful to distinguish learning activities that do have a practical (laboratory or field) component from the broader notion of ‘active’ learning where students are engaged in activities (group discussions, data analysis, model building) that do not involve specialised locations or apparatus. Collection and analysis of data by remote use of apparatus is becoming a more common type of practical work, and the collection and analysis of data produced by computer simulations may be seen as a borderline case of ‘practical’ work. In the context of the reported project the practical work undertaken was primarily the construction of electrical circuits by small groups of students to test their predictions and provide empirical evidence to inform discussion of their ideas.

Teaching about Models and Analogies: A model is a representation of something in another form (e.g. a mathematical representation of a pattern observed in measurements of some physical quantity) which is considered to be able to stand for some aspect of what is being modelled. Scientific knowledge is often formulated as models, and the development of scientific knowledge often involves the construction and testing of various kinds of models. Analogies are comparisons of structural similarity between different systems (such as comparing nucleus-electron interactions in an atom with sun-planet interactions in a solar system). The creative aspect of scientific work, which generates ideas to critique and test, often draws upon analogies as novel ways of thinking about a target phenomenon or concept. The topic of electricity is often taught at school level using teaching models and analogies, but teaching about models and analogies involves making explicit the roles of the models and analogies and acknowledging how this reflects aspects of authentic scientific practice.

Teaching about the Nature of Science: Teaching about the nature of science complements teaching about the output of the scientific process (i.e. consensus models and theories that are considered the ‘content’ to be taught) and is widely considered to be important both for future scientists and as part of the education of any scientifically literate citizen. Teaching about the nature of science includes consideration of both the fundamental commitments of science that inform what might be called the scientific attitude, or scientific values, and the processes of science. The latter goes beyond scientific method to appreciate both the way scientific knowledge may be robust yet always open to reconsideration, and how scientific knowledge develops from the mediation of creative human thinking through social/institutional processes. In the context of the reported project the main focus of teaching about the nature of science concerned how models are used as tools for developing explanations and for making predictions that can then be tested empirically.