Evidence-informed approaches to teaching science at junior high school level: outcomes in terms of student learning

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ABSTRACT
This study provides evidence about the feasibility of improving student learning against specified curriculum goals, when the design of that teaching is informed by evidence from science education research. Three teaching sequences were designed by a group of researchers and teachers, drawing upon insights from research on students' learning in particular domains. The teachers then implemented the teaching sequences in their own classrooms. Student learning was evaluated using a pre-test post-test design. Baseline data were collected from other classes of similar students in the same schools, using the same test instruments, but following the school's usual teaching approach. This paper presents evidence that students' understanding of target scientific concepts was significantly better following the designed teaching, than following the schools' usual approaches. In future work, the teaching sequences will be implemented and evaluated in classrooms where the teachers were not involved in the design of the teaching.

The problem addressed in this paper

The literature on students' learning of scientific concepts is extensive (Pfundt & Duit, 2001). However, the impact of this research on the practices of day-to-day science teaching has not been great (Duit & Treagust, 1998). Furthermore, some are sceptical as to whether teaching based on information about students' existing knowledge leads to gains in students' understanding (e.g. Matthews, 1997).

Although there are some studies in the literature that do provide evidence of improvements in student learning against specified goals, following research-informed teaching interventions (for example: Brown and Clement, 1991; Tiberghien, 2000; Viennot and Rainson, 1999), such studies generally say rather little about the role of the teacher in implementing the teaching. Furthermore, the teacher in these studies has often worked very closely, over an extended period of time, with the research team. There is little, or no, evidence that teachers less closely involved with the research process can replicate the improvements in student learning.

The study reported in this paper was designed to provide evidence about the feasibility of improving student learning against specified curriculum goals, when the design of the teaching is informed by insights from research on students' learning. The study consists of two phases. During the *Development phase*, groups of teachers and researchers worked together to design, implement and evaluate short teaching sequences for junior high school students. An important aspect of the evaluation addressed the extent to which students following the designed teaching approach attained a richer understanding of the target conceptual content, compared to other students of the same ability following the school's usual approach. During the *Transfer phase*, those teaching sequences where there appeared to be clear evidence of enhanced student learning were implemented by teachers not involved in the design of the teaching sequence. This teaching was evaluated in the same way as in the Development phase.

This paper reports findings from the Development phase.

Design and methodology

Three short teaching sequences were designed, implemented and evaluated. Each sequence was prepared collaboratively by a group of teachers (3 biology, 3 chemistry, 3 physics) and university-based researchers working together. The teaching sequences were aimed primarily at pupils aged between 11 and 14, and lasted for around 6 hours. The schemes focused upon introductory ideas about plant nutrition, the process of modelling change in terms of a simple particle model of matter, and introductory ideas about electric circuits. These areas were selected on the grounds that there is a significant body of empirical research on students' learning in each area, together with studies describing the design and evaluation of teaching approaches.

The overall shaping of the teaching sequences was informed by a social constructivist perspective on learning (Driver et al., 1994; Leach and Scott, 2003), with particular attention being given to the different communicative approaches (Scott and Mortimer, 2002; Mortimer and Scott, in press) to be taken by the teacher in promoting learning. In addition an analysis of the particular learning demands (Leach and Scott, 2002) was made for each of the topic areas, drawing on specific research evidence about students' learning in those areas, and instructional activities were planned to address those demands. Each participating teacher then implemented the teaching sequence with at least one class.

The implementation of the teaching sequences was evaluated using multiple data sources. Students' learning against specified goals was measured by comparing responses to diagnostic questions set prior to teaching, immediately after teaching, and after a delay of several weeks. Furthermore, the same diagnostic questions were completed by groups of students in parallel classes, who had followed the school's regular teaching approach, thereby providing baseline information on student attainment. The schools viewed the students in these 'baseline' groups as similar in ability to the students in the 'case study' groups. This aspect of the evaluation will be presented in this paper. We have not included information from the delayed post-tests as there is evidence in several cases that unplanned, relevant teaching took place between the post-test and delayed post-test.

In addition, all lessons were video- and audio-recorded and the tapes were used to analyse the 'staging' of the lessons by each teacher. This analysis was made in terms of four classes of communicative approach, derived from categorising the teacher-student interactions along each of two dimensions: interactive/non-interactive and dialogic/authoritative (Mortimer and Scott, in press). Further analyses of teacher-student interactions were made for each teacher, in other lessons, as they taught a topic offering a similar kind of learning demand, but following their normal teaching approach. The video and audio records were also used to make a record of the sequence in which scientific ideas were introduced during the teaching, to establish the extent to which the teacher followed the planned teaching sequence. This aspect of the evaluation will be reported elsewhere.

We are currently in the process of evaluating the implementation of two of the three teaching sequences by teachers not involved in their initial design, as part of the transfer phase. The purpose of this is to provide evidence as to whether any learning improvements, noted when the teaching sequences are implemented by the teachers involved in their design, can be replicated more widely.

Sample

9 teachers worked with us on the Development Phase of the project. All were at the early or middle stages of their careers, with only 1 holding a significant middle management position in a science faculty. 6 are female and 3 are male. The teachers were selected on the grounds that they are viewed by us, and their peers, as being enthusiastic and able practitioners, whilst having no special training in science education research. Their schools are located in a variety of different communities in the North of England, ranging between inner-city multicultural and affluent suburban.

Information about the sample is presented in Table 1:

Table 1: Sample information

	Reference	*Teacher:*	*Case Study Class*[1] *n=*	*Baseline class N=*
Biology	B1V	Vic	27	27
	B2C	Chris	28	30
	B3S	Sam	29	26
Chemistry	C1L	Lee	28	Not available[2]
	C2A	Andy	20	Not available[2]
	C3S1	Sarah	18	Not available[2]
	C3S2	Sarah	17	Not available[2]
Physics	P1A	Ashley	20	20
	P2D1	Drew	29	22
	P2D2	Drew	28	22
	P3S	Sandy	23	26

Notes:

1 *n refers to the number of students responding to the diagnostic questions*

2 *No baseline information was available for the chemistry teaching sequence. None of the 3 schools usually addressed the modelling of physical and chemical change in any one teaching unit; rather, the teaching was spread across several units.*

Methods used for evaluating students' learning

A group of diagnostic questions, based upon questions previously used and reported in the literature, was designed for each teaching sequence. The questions provided opportunities for students to use the core conceptual models introduced in each teaching sequence. Where possible, the same questions were used in the pre- and post-tests, and any given idea was probed through more than one question. However, this was not always feasible:

- In some cases, the group of researchers and teachers judged it inappropriate to include questions in the pre-test addressing technical content not yet encountered by students. For example, it was not judged appropriate to ask students questions involving quantitative measurements of electric current prior to teaching.

- A limited number of questions was used to minimise student fatigue and boredom, and to address teachers' concerns about taking up too much class time with testing.

The questions tend to be in two parts. The first part involves students in making a prediction of some kind (the behaviour of lamps in a simple circuit, the mass of a solution on dissolving), and this is followed by an opportunity for students to explain their prediction. Students' responses were coded according to whether they made a correct prediction or not, and the extent to which their explanation drew upon the target conceptual content of the teaching sequence.

Students' responses across groups of questions are reported in this paper. Sample questions are shown in Appendices 1, 2 and 3.

The teaching sequences in outline

The three teaching sequences share the following common features in their design:

- A detailed content analysis of the area was conducted, including an analysis of the compulsory school curriculum. Learning demands (Leach and Scott, 2002) were identified.
- Teaching goals were written, to address the learning demands.
- Teaching activities were designed to address those teaching goals.
- The teaching sequence began and ended with students completing diagnostic questions.
- Opportunities were planned explicitly for different kinds of teacher/student discourse, with different purposes. This aspect of the teaching was discussed in the planning meetings, and referred to in the teaching scheme. Information about likely student difficulties and possible teaching strategies was also discussed, and referred to in the teaching scheme.

The teaching sequences are available on-line at:
http://www.education.leeds.ac.uk/devt/research/scienceed/ epse_teach_resources.htm

The chemistry teaching sequence: Modelling change

The chemistry teaching sequence was the first to be produced and implemented. The national curriculum for pupils aged 11-14 in England states that pupils should be taught to explain physical and chemical change in terms of particles, and to appreciate that mass is conserved in physical and chemical change processes. However, given that each of the three teachers' schools organised this part of the curriculum differently it was not possible to produce a unit that could be used across all the schools. Instead, the teachers and researchers agreed to produce a short revision module for use with pupils after all content had been covered, to assess their understanding and to reinforce their ability at using a simple particle model to explain actual physical and chemical change processes.

A review of the literature on teaching and learning particulate models of matter was conducted, and the following characteristic patterns in students' reasoning were identified (Andersson, 1991; CLIS, 1987; Driver et al., 1994; Holding, 1987; Méheut, 1998; Mirzalar-Kabapinar, 1998; Novick and Nussbaum, 1981; Séré, 1985; Vollerbregt (1998):

- Gases are often not thought of as ‘substantial’ in the same way as solids and liquids are (for example, they may be thought of as having no mass or negative mass);
- *Mass*, *volume* and *density* are often not differentiated in students’ explanations of physical and chemical change;
- Matter is thought to *surround* particles (for example, the spaces between *particles* in air are thought to contain *the air itself*);
- 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 the conceptual analysis of the curriculum, and the review of literature, learning demands were identified and teaching goals were developed. The teaching goals for the teaching sequence were:

- To assess pupils’ understanding of the particle models of matter already introduced, and to assess how pupils use these to explain some simple physical and chemical change phenomena;
- To review the particle model already taught, and, if appropriate, to extend that model to make it more coherent by introducing features such as simple intermolecular interactions;
- To provide pupils with opportunities to use the model for themselves to model simple, and more complex, change processes, and to provide contexts for the teacher to support pupils’ attempts at modelling.

The teaching sequence consisted of 4 lessons. The design of the teaching sequence drew upon insights from the research literature. Activities were designed in order to provide contexts for teacher-student talk in addressingthe learning demands. Some of these activities drew heavily upon activities previously reported in the research literature. Notes were provided for the teachers about likely student difficulties and possible ways of responding to students’ reasoning. During the first lesson, students worked in pairs on diagnostic questions in which they had to make predictions about macroscopic properties such as mass and volume during physical and chemical change processes, and to explain those predictions in whatever way they wished. At the beginning of the second lesson, the teacher reviewed the simple particle model already introduced to pupils. The model introduced in the teaching sequence had some features not normally included in teaching for pupils aged 11-14 in England, such as attractions between particles, in order to allow pupils to propose more coherent explanations. The model draws heavily on that articulated by Vollerbregt (1998). During the remainder of the second lesson and the third lesson, the teacher demonstrated to pupils how the model could be used to explain some of the phenomena introduced to pupils during the first lesson. Pupils were also asked to work in groups to generate their own explanations using the model, for the teacher to evaluate. During the final lesson, pupils worked on their own on more diagnostic questions which required them to explain physical and chemical changes in terms of the model. Some of these contexts had been discussed during lessons 1, 2 or 3, and some were new.

On implementation, the teaching sequence was found to have significant weaknesses, mainly concerning the extent to which teaching *activities* had been developed and embedded into workable *whole lessons* that were motivating for students. Drawing upon our experience of the shortcomings of the chemistry teaching sequence, the design and presentation of the physics and biology teaching sequences was modified considerably.

The biology teaching sequence: Plant Nutrition

The Science National Curriculum for England states that all pupils aged 11-14 should be taught that:

- Plants need carbon dioxide, water and light for photosynthesis, and produce biomass and oxygen
- Photosynthesis can be summarised as a word equation
- Nitrogen and other elements, in addition to carbon, oxygen and hydrogen, are required for plant growth.

Pupils at this age are also taught that plants carry out aerobic respiration.

These ideas are revisited between the ages of 14 and 16 in slightly more detail. At this stage the curriculum states that pupils should be taught:

- The reactants in, and products of, photosynthesis
- How the products of photosynthesis are utilised by the plant
- The importance to healthy plant growth of the uptake of minerals.
-

In addition they are taught that the rate of photosynthesis may be limited by light intensity, carbon dioxide concentration and temperature.

Because of the overlap of the curriculum between ages 11-14 and 14-16, it was possible to design a teaching sequence which could be used across both age ranges. Two teachers, working with the 11-14 age group, used the basic sequence. The third teacher, working with the 14-16 age group, used the same basic sequence but moved through it more quickly and included a little more detail in the later stages. The teaching was then extended to explain rate-limiting factors but this work was not included in the teaching sequence and did not form part of our evaluation.

A review of the literature on teaching and learning about plant nutrition was conducted (Driver et al., 1993; Barker 1985; Barker, 1986; Barker and Carr, 1989a,b; Canal, 1999; CLIS, 1987; Eisen and Stavey, 1993; Haslam and Treagust, 1987; Kinchin, 2000; Roth 1985; Stavy et al, 1987; Wandersee, 1983; Wood-Robinson, 1991). The following characteristic patterns in student reasoning were identified:

- A view of nutrition, based on animal nutrition, as the ingestion of ‘food’ and the idea that ‘food’ is absorbed from the soil through the roots of a plant.

- A lack of differentiation between photosynthesis and respiration (the idea that photosynthesis is the plant equivalent of respiration; that sugar provides energy not biomass).
- The idea that sunlight is a reagent, not a source of energy
- A lack of recognition of the chemical basis of biological processes, and that simple ‘ingredients’ such as water and carbon dioxide can be combined (through chemical reactions) to produce more complex materials.
- A difficulty in accepting that gases can be a source of biomass.
- A lack of recognition that mass/matter is conserved in biological processes.
- A lack of recognition of the site of biological processes within an organism.

Based on the conceptual analysis of the curriculum, and these characteristics students’ reasoning, learning demands were identified and teaching goals developed. The teaching goals for the teaching sequence were:

1. *To open up the students’ own ideas* about food (what it is, where it comes from, what it is needed for) and to encourage students to discuss and question these; to develop an explicit understanding of the distinction between sources of food and functions of food.
2. *To make the implausibility of the scientific explanation explicit*: to problematise the simple scientific explanation that carbon dioxide combines with water to produce sugar in photosynthesis.
3. *To demonstrate that apparently implausible physical processes do indeed happen*:
    - that carbon dioxide gas does have mass
    - that a gas and a liquid can combine to produce a solid
    - that simple molecules (water and carbon dioxide) can combine to produce a complex molecule (sugar)
    - that matter is conserved in chemical change proceses
4. *To develop a simple model of photosynthesis* based upon the above physical principles, and to make this model plausible, demonstrating how sugar is produced in the leaf.
5. *To show how this sugar can be converted into different food types* and assimilated into the biomass of plants, making explicit the role of minerals in the soil:
    - Glucose molecules can combine to produce different types of carbohydrate
    - Glucose molecules can combine in different ways to produce fats
    - Glucose molecules can combine with nitrogen to produce proteins
    - Glucose molecules can combine with magnesium to produce cholorophyll
6. *To assess and consolidate the learning* by revisiting the source and function of food in plants and animals.

In Lesson 1 students initially worked in small groups to make reasoned predictions about a number of scenarios relating to plant growth. The groups then went on to consider their ideas about food. A whole class ‘brainstorming’, during which the students’ different ideas about food were made explicit followed. The teacher recorded all ideas. However, misconceptions were not noted or addressed at this point. Rather, groups were given the opportunity to reconsider and, if they wished, to change their earlier predictions. In Lesson 2, scientific ideas about plant nutrition were introduced. Students were encouraged to problematise the simple scientific explanation presented to them and to identify those aspects of this explanation, which seemed implausible. A number of statements were provided to support students in this task. Students' ideas were then fed back to the whole class through the teacher. During Lesson 3, apparently implausible physical aspects of photosynthesis were presented and reviewed. These include the ability of a gas and a liquid to combine to form a solid, the fact that carbon dioxide (a gas) has mass, and the fact that simple molecules can combine to produce complex molecules.

In Lesson 4, ideas presented and developed over the last three lessons were reviewed and the need for energy in chemical reactions was demonstrated. These ideas were then drawn together to present a simple scientific model for the production of sugar by the process of photosynthesis, including the role of sunlight. This explanation was recorded formally in the students' exercise books. Students returned to their initial predictions, answering a series of focused questions, in order to consolidate and assess their understanding.

Lesson 5 completed the story of plant nutrition by considering how sugar, produced by photosynthesis, is used by a plant. A simple explanation of how glucose can be converted into other food types (including the role of minerals taken up from the soil) was presented and students completed a worksheet designed to consolidate their understanding of how this can lead to an increase biomass. The use of glucose in the process of respiration, for the release of energy, was also presented. Finally, students completed a table comparing plant and animal nutrition.

The physics teaching sequence: Electric circuits

The science national curriculum for England requires that pupils aged 11-14 are taught that in simple electric circuits: energy is introduced to the circuit via the battery; energy is transferred to the surroundings through resistive components such as bulbs; a flow of charge provides the means for transferring energy around the circuit; increasing the number of batteries in a circuit, increases both the energy introduced to the circuit and the size of the current; adding resistive components (such as bulbs) to a circuit reduces the size of the current and results in energy being shared between the components. This electric circuit model is developed in subsequent phases of the national curriculum through introduction of the concept of voltage. All three teachers in the working group covered these ideas somewhere within their 11-14 school science curriculum, and so it was possible to develop a single teaching sequence for use in all three schools.

A review of the literature on teaching and learning about simple electric circuits was conducted and the following characteristic patterns in students' reasoning were identified
(see, for example: Psillos, 1998; Shipstone, 1988).

- The circuit is not viewed as a *whole system*, with changes occurring virtually simultaneously in all parts. For example, when a switch is closed charges are set into motion in all parts of the circuit together. Instead, students often explain effects in terms of *sequential* models, where any disturbance travels in one direction, affecting circuit components in succession. For example, when an extra resistive component (such as a bulb) is added in series to a circuit, students often predict that the ‘first component’ after the battery gets most, or all, of the energy.

- Students often think about electric circuits in terms of a *source* (the battery) and a *consumer* (for example, a bulb). This can lead to problems. For example:
    - The charge which constitutes an electric current is considered to originate in the battery (the *source*)
    - The battery is considered to provide a fixed electric current. When a battery is added to a circuit the extra current is thought to come from the additional battery (the *source*).
    - Electric current and energy are not differentiated, with students suggesting that the current is use up in a bulb (the *consumer*).
- Electric current is taken as a measure of how fast the charges are moving, rather than of how much charge passes any point in a circuit per unit time.
- The size of the electric current is estimated to be less in high resistance parts of a circuit (such as a bulb filament) than in other parts (such as the connecting leads).

Based upon the conceptual analysis of the curriculum, and the review of students’ reasoning, learning demands were identified and teaching goals developed. Four teaching goals were identified for the electricity sequence. The first three relate to conceptual goals, whilst the fourth has an epistemological focus:

1. To *introduce, and support the development of,* the ideas that:
    - an electric current consists of a flow of charge
    - the charges originate in the circuit itself
    - the electric current transfers energy around the circuit
    - components such as bulbs introduce resistance to the circuit. The resistance restricts the flow of charge, reducing the current flowing around the whole circuit and resulting in heating and lighting as the current passes through the resistance.

2. To *differentiate between*:
    - the concepts of charge, current, energy, emphasising that the electric current is not consumed, rather, it is the energy which is transferred, in resistances, to the surroundings

3. To *emphasise throughout* that:
    - Electric circuits behave as whole systems such that a change in one part of the circuit affects all other parts of the circuit simultaneously.

4. To *introduce, and support the development of,* the idea that:
    - the scientific electric circuit model, based on concepts of charge, current, resistance, energy, can be used to predict and explain the behaviour of a wide range of simple circuits.

The teaching sequence was designed to address these goals and consisted of four lessons. In Lesson 1, two diagnostic questions (Millar et al, 2003) were set for the students to work through individually, with a view to the teacher being able to probe their initial understandings of a simple electric circuit. The basic elements of the electric circuit model were then introduced via a teaching analogy. The approach taken in the teaching sequence emphasises the importance of introducing the teaching analogy systematically, making explicit links between the home and target domains (Glynn, Duit, & Thiele, 1995). In addition, it was decided that rather than include a number of different teaching analogies in the sequence (each of which demands the same careful introduction and development), the focus would be on just one.

The particular teaching analogy selected targets the charges-carrying-energy aspect of the electric circuit model, thereby addressing the key teaching goal of differentiating between charge and energy. In the analogy the electric circuit is represented in terms of a continuous line of vans (charges), collecting loaves of bread (energy) at a bakery, and carrying them round to a supermarket (bulb) where they are delivered and dissipated. There has been considerable debate in the literature about the advantages and disadvantages of specific teaching analogies, in the context of electric circuits, (see, for example, Schwedes and Dudeck, 1996). We recognise that the charges-carrying-energy analogies have their drawbacks, relating in particular to the detail of what happens during the transient phases after a circuit is completed or broken. We came to the conclusion, however, that such weaknesses are unlikely to be detrimental to student progress during the first steps of developing an electric circuit model. The overall sequence was therefore designed so that the same teaching analogy was drawn upon throughout the four lessons, as the teacher supported the students in coming to an understanding of the effect on the electric current and energy transfer, of changing the numbers of cells and bulbs.

Furthermore, in designing the various teaching activities (including demonstrations, practical activities and so on) explicit attention was paid to the kinds of interaction between teacher and students *around* those activities. Thus in some situations, the intention might be that the teacher introduces new ideas. At other times an activity might be planned with the central aim of providing an opportunity for students to talk through the ideas for themselves with the teacher probing and supporting that discussion. These different kinds of talk were explicitly referred to, and highlighted with a set of simple icons, in the teaching scheme.

Findings

In this section, we present findings from the pre- and post-tests completed by students following the three designed teaching sequences, compared with baseline information from students in comparable classes in the same schools following the school's usual programme of instruction (where such information is available).

Evaluation of the Chemistry teaching sequence

Table 2 shows students' results in pre- and post-tests, where information is available. The pre- and post-tests all contained questions where students had to make predictions about changes in the macroscopic characteristics of a system (for example, mass) following a physical or chemical change. They were then given an opportunity to explain their prediction, and in each case a particulate explanation as introduced in the teaching sequence could be used. Data are presented about the number and percentage of students using a particulate model, consistent with that introduced in the teaching sequence, to explain their prediction. [In a small number of cases, a model was used appropriately to explain a prediction that was incorrect; such cases are indicated.]

Five questions were used to evaluate students' understanding of modelling change; an example can be found in Appendix 1. Students' responses were avaraged across the 5 questions. For example, in case study C1L, the post-test figure 6.0 'consistent uses of the model' indicates that, out of the group of 28 students answering 5 questions, the mean number using a complete model consistent with that taught was 6.0. This in turn represents 23.1% of the total number of students.

Table 3: Evaluation of students' learning following implementation of the chemistry teaching sequence

	PRE-TEST [PREDICTION]			PRE-TEST [EXPLANATION]				POST-TEST [PREDICTION]			POST-TEST [EXPLANATION]			
	n	Correct	Incorrect	n	Consistent	Consistent (wrong context)	Other	n	Correct	Incorrect	n	Consistent	Consistent (wrong context)	Other
C1L	28	12.0 *42.9*	16.0 *57.1*	28	0.7 *2.4*	0 *0*	27.3 *97.6*	26	17.0 *65.4*	9.0 *34.6*	26	6.0 *23.1*	1.3 *5.1*	18.7 *71.8*
C2A	20	9.0 *45.0*	11.0 *55.0*	20	1.0 *5.0*	0.7 *3.3*	18.3 *91.7*	20	16.7 *83.3*	3.3 *16.7*	20	12.3 *61.7*	1.7 *8.3*	6.0 *30.0*
C3S1	18	3.0 *16.7*	15.0 *83.3*	18	0.3 *1.9*	0.3 *1.9*	17.3 *96.3*	17	9.0 *52.9*	8.0 *47.1*	17	4.0 *23.5*	2.0 *11.8*	11.0 *64.7*
C4S2	17	5.3 *31.4*	11.7 *68.6*	17	0.0 *0.0*	0.0 *0.0*	17.0 *100*	16	9.7 *60.4*	6.3 *39.6*	16	6.3 *39.6*	2.0 *12.5*	7.7 *47.9*

Notes

Percentages are shown in italics. 'C1L' indicates Chemistry case study 1,taught by Lee. Case Study 2 was taught by Andy, and Case Studies 3 and 4 were both taught by Sarah.

Lee did not attempt to follow the detail of the teaching sequence, as he had reservations about the feasibility of some of the activities for his students. The teaching implemented by Andy did follow the teaching sequence, though there were some significant differences in the ordering of content, and the detail in which it was covered. Students in Andy's classes were significantly better at making predictions about macroscopic behaviour, and explaining those predictions using an appropriate model (χ^2; $p<0.001$), after teaching. The increase in the number of pupils using a particle model of matter to explain predictions, whether correct or incorrect, between the pre- and post-test was from 21.6% to 39.6%.

The absence of baseline information about students' learning following the schools' usual teaching approaches makes it difficult to judge the success of the designed teaching at promoting students' learning. The gains in student learning, though significant, were not particularly great. Information from interviews with the three teachers, together with our analysis of the 'staging' of the teaching, leads us to make the following observations:

- Although all three teachers were enthusiastic about the teaching sequence in pre-implementation interviews, Lee and Sarah were not particularly positive after implementation. Andy was more positive, though all the teachers felt that the lessons needed considerably more work to make them motivating for students, and practical within the time available.
- Sarah felt that the teaching approach developed in the chemistry teaching sequence did not fit with her usual classroom approach. In an interview after she had implemented the teaching, she stated that she had felt considerable tensions in attempting to implement the teaching. Nonetheless, she spoke with conviction about what she had learnt about her pupils' lack of understanding of core concepts as a result of implementing the teaching, and suggested how her school's usual approach to the introduction of particle models to explain physical and chemical change could be improved.
- None of the teachers introduced the central conceptual content of the chemistry teaching sequence in the way that had been agreed.

For these reasons, we would not claim that the teaching as enacted was strongly informed by research evidence, and we are not using the chemistry teaching sequence in the Transfer phase.

Evaluation of the Biology teaching sequence

Table 3 shows students' results in pre- and post-tests, where information is available. The pre- and post-tests all contained questions where it would be appropriate to draw upon the scientific model of plant nutrition taught in the teaching sequence (See Appendix 2). In addition, one question required students to make a prediction (for example, the effect of light on the number of starch grains in *Chlamydomonas*).

Data are presented about the predictions made by students, and the way in which the model introduced in the teaching was used. Responses were coded according to whether students used a model consistent with that presented in the teaching, or used an incomplete but consistent model, or made some other form of response. Students' use of the model of plant nutrition, introduced during teaching, have been averaged in a similar way as with the chemistry teaching sequence.

Table 3: Evaluation of students' learning following implementation of the biology teaching sequence

	PRE-TEST				POST-TEST (PREDICTION)				POST-TEST (USE OF MODEL)			
	n	Consistent	Incomplete	Other	n	Consistent	Incomplete	Other	n	Consistent	Incomplete	Other
B1V	27	6.3 *23.5%*	5.0 *18.5%*	15.7 *58.0%*	27	21.0 *77.8%*	2.0 *7.4%*	4.0 *14.8%*	27	8.3 *30.6%*	8.3 *30.6%*	10.5 *38.9%*
Baseline	27	7.7 *28.4%*	6.7 *24.7%*	12.7 *46.9%*	23	14.0 *60.9%*	3.0 *13.0%*	6.0 *26.1%*	23	1.8 *7.6%*	6.0 *26.1%*	15.3 *66.3%*
B2C	28	10.3 *36.9%*	7.7 *27.4%*	10.0 *35.7%*	28	24.0 *85.7%*	2.0 *7.1%*	2.0 *7.1%*	28	18.0 *64.3%*	6.8 *24.1%*	3.3 *11.6%*
Baseline	30	8.0 *26.7%*	14.0 *46.7%*	8.0 *26.7%*	29	26.0 *89.7%*	2.0 *6.9%*	1.0 *3.4%*	29	7.5 *25.9%*	11.3 *38.8%*	10.3 *35.3%*
B3S	23	6.3 *27.5%*	6.0 *26.1%*	10.7 *46.4%*	29	27.0 *93.1%*	2.0 *6.9%*	0.0 *0.0%*	29	21.5 *74.1%*	4.5 *15.5%*	3.0 *10.3%*
Baseline	0	Not available			26	18.0 *69.2%*	8.0 *30.8%*	0.0 *0.0%*	26	10.0 *38.5%*	4.0 *15.4%*	12.0 *46.2%*

Notes

Percentages are indicated in italics. B1V indicates Biology case study 1, taught by Vic. Case study 2 was taught by Chris, and Case Study 3 was taught by Sam.

The questions used to evaluate students' understanding of plant nutrition can be found in Appendix 2.

On the basis of the information in Table 3, we make the following claims:

- There is no strong evidence for different levels of understanding of plant nutrition between students in case study and baseline groups in Vic and Chris's schools prior to teaching (χ^2; p>0.01[2]). Pre-test baseline data are not available in Sam's school.
- There is no evidence that students in the case study groups were better at making predictions about plant nutrition than those in the baseline groups following teaching (χ^2; p>0.01 in all cases).
- However, there is evidence that students in each of the case study groups, immediately after teaching, drew upon a scientifically consistent model of plant

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[2] In order to calculate χ^2 students' responses for each question were totalled. This process provided larger samples that can be considered independent. In the case of B1V, the null hypothesis is *'There is no difference between the way in which students use a model of plant nutrition in the baseline and case study groups prior to teaching.* Using the following data, the probability that the null hypothesis is true is 0.032:

	Consistent	Incomplete	Other	*Totals*
B1V observed	31	23	30	*84*
B1V expected	26.6	31.4	26.1	
Baseline	24	42	24	*90*
Baseline expected	28.4	33.6	27.9	
Totals	*55*	*65*	*54*	*174*

nutrition more often than did students in the baseline groups (χ^2; $p<0.001$ in all cases).

Evaluation of the Physics teaching sequence

Table 4 shows students' results in the pre- and post-tests, where information is available. The pre and post-tests contained questions where it would be appropriate to draw upon the scientific model of the behaviour of simple series circuits taught in the teaching sequence (see Appendix 4). The questions were structured so that students had to make a *prediction* about the behaviour of a given circuit (e.g. would the bulb light and how brightly?) followed by an *explanation* for that behaviour. Students' responses in the 2 pre-test questions and 6 post-test questions were averaged in a similar way to responses in the biology and chemistry case studies. Data are presented about the number and percentage of students making correct and incorrect predictions, and the number and percentage using an explanatory model consistent with its presentation in the teaching, or using an incomplete but consistent model, or not using the model (or using a model inconsistent with that introduced in the teaching), or providing no/other responses.

Prior to this sequence, the students had encountered elementary work on the behaviour of electric circuits in terms of 'what happens' but had not studied any explanations for that behaviour in terms of current, charge and energy. For this reason the pre-test did not include questions explicitly requiring students to use these concepts.

The questions used to evaluate students' understanding of electric circuits can be found in Appendix 4.

Table 4: Evaluation of students' learning following implementation of the physics teaching sequence

	PRE-TEST (PREDICTION)			PRE-TEST (USE OF THE MODEL)				POST-TEST (PREDICTION)			POST-TEST (USE OF THE MODEL)			
	n	Correct	Incorrect	n	Consistent	Incomplete	Other	n	Correct	Incorrect	n	Consistent	Incomplete	Other
P1S	23	14.6 *62.3*	8.3 *37.7*	23	1.0 *4.3*	5.0 *21.7*	17.0 *73.9*	23	21.2 *92.0*	1.8 *8.0*	23	1.0 *4.3*	9.8 *42.8*	12.2 *52.9*
Baseline	*26*	20.3 *78.2*	5.7 *21.8*	26	4.0 *15.4*	10.0 *38.5*	12.0 *46.2*	26	22.3 *85.9*	3.7 *14.1*	26	0.0 *0.0*	5.5 *21.2*	20.5 *78.8*
P2D1	27	19.3 *71.6*	7.7 *28.4*	27	1.0 *3.7*	12.0 *44.4*	14.0 *51.9*	29	25.3 *87.3*	3.7 *12.3*	29	*4.5* *15.5*	16.3 *56.3*	8.2 *28.2*
P3D2	*28*	16.7 *59.5*	11.3 *40.5*	28	1.0 *3.6*	9.0 *32.1*	18.0 *64.3*	28	23.8 *85.1*	4.2 *14.9*	28	4.3 *15.5*	10.7 *38.1*	13.0 *46.4*
Baseline	*22*	*10.3* *47.0*	*11.7* *53.0*	*22*	*0.0* *0.0*	*8.0* *36.4*	*14.0* *63.6*	*20*	*19.0* *95.0*	*1.0* *5.0*	*20*	*0.2* *0.8*	*3.8* *19.2*	*16.0* *80.0*
P4A	*20*	*15.7* *78.3*	*4.3* *21.7*	*20*	*0.0* *0.0*	*6.0* *30.0*	*14.0* *70.0*	*20*	*19.7* *98.3*	*0.3* *1.7*	*20*	*5.7* *28.3*	*11.7* *58.3*	*2.7* *13.3*
Baseline	*20*	*17.0* *85.0*	*3.0* *15.0*	*20*	*0.0* *0.0*	*9.0* *45.0*	*11.0* *55.0*	*20*	*18.2* *90.8*	*1.8* *9.2*	*20*	*0.2* *0.8*	*4.8* *24.2*	*15.0* *75.0*

Notes

Percentates are shown in italics. P1S indicates that Physics case study 1 was taught by Sandy. Case studies 2 and 3 were taught by Drew, and Case Study 4 was taught by Ashley.

On the basis of the information in Table 4, we make the following claims:

- There is no strong evidence for different levels of understanding of electric circuits between students in case study and baseline groups in any school prior to teaching (χ^2; $p>0.01$ in all cases for explanations and predictions, with the exception of predictions in P2D1).
- There is no evidence that students in the case study groups were better at making predictions about the behaviour of electric circuits than those in the baseline groups after teaching (χ^2; $p>0.01$).
- However, there is evidence that students in each of the case study groups, immediately after teaching, drew upon a scientifically consistent model of the behaviour of electric circuits more often than students in the baseline groups (χ^2; $p<0.001$ for all groups). Even though all groups' predictions improve by a similar amount after teaching, it was striking that students' explanations in the three baseline groups made use of *fewer* elements of the taught model after teaching than in the pre-test. By contrast, the case study students' explanations made a wider use of elements of the model after teaching. Explanations using most of the elements of the model account for less than 1% of the answers of the baseline group students after teaching, while accounting for between 4.3% and 28.3% of the case groups students' answers.

Discussion

To what extent can we claim that the teaching designed and implemented in this study resulted in improvements in students' learning against specific curriculum goals? Our analysis of the physics and biology case studies suggests that the teaching, as implemented, covered content in a way that was consistent with our identification of learning demands and teaching goals. To that extent, we would claim that the teaching as enacted was informed by insights from research on teaching and learning science. However, in the case of the chemistry case studies, the teaching *as implemented* did not cover content in a way that was consistent with our identification of learning demands and teaching goals. We do not, therefore, claim that it was informed by research evidence.

In this paper we have presented evidence to support the following claims:

1. The physics and biology teaching sequences were no better or worse than the schools' usual teaching approaches at enabling students to complete successfully diagnostic questions requiring factual recall (e.g. predicting the illumination of a bulb or the number of starch grains in a cell).
2. However, both the physics and biology teaching sequences, as implemented, resulted in students being significantly better than others following the schools' usual teaching approaches at using conceptual models of electric circuits and plant nutrition respectively in diagnostic questions.

We were not able to collect an appropriate data set to investigate students' retention of conceptual understanding over a more prolonged period of time, or their achievement in future science learning.

It is, of course, possible that the differences in student learning reported between the case study and control groups are due to factors other than the extent to which the teaching was informed by insights and evidence from research on teaching and learning science. We think that there are two main possibilities:

- *Testing bias*. It is likely that our test instruments were biased towards the content of the designed teaching, compared to the school's normal teaching. Post-test results in the physics case studies reinforce our suspicions of testing bias, given that students used *less* elements of a scientific model of the behaviour of a circuit after teaching in the baseline case study classes. This indicates that teaching may have focused upon making correct predictions about the behaviour of circuits, rather than providing explanations for that behaviour. However, our test instruments do address conceptual content identified in the English national curriculum. To that extent we would defend the use of the instruments to provide evidence that teaching informed by insights and evidence from research on teaching and learning science can result in improvements in student learning against specific curriculum goals.
- *Lack of comparability between students and teachers in case study and baseline groups*. There is no evidence to support the view that students in case study groups were more able than students in baseline groups, based upon pre-test data. However, it is possible that the teachers that we worked with may well achieve better results amongst their students against stated curriculum goals than the teachers teaching the baseline groups. Once more data are available, we will evaluate this possibility further. However, we are encouraged by the fact that in all of the case studies analysed so far, students following the designed teaching sequences perform significantly better on diagnostic questions testing for

conceptual understanding than their peers following the school's usual teaching, yet there are no significant differences in students' performance on diagnostic questions requiring factual recall.

We remain optimistic that, as the study progresses, we will be in a position to make firmer claims about the feasibility of achieving improved student learning against stated curriculum goals through the implementation of teaching informed by insights and evidence from research on science teaching and learning. We are also encouraged by the enthusiasm of teachers interviewed so far to adopt the physics and biology teaching sequences because they are viewed as better at meeting curriculum content objectives, and more enjoyable for students, than the usual approaches used.

Preliminary data analysis indicates that teachers using the biology and physics teaching sequences tended to use more conceptually-focused talk in the classroom than usual, and that more of that talk was dialogic in nature in that both students and teachers had some control over the content of the talk. We are optimistic that, after further data analysis, we will be in a position to present evidence that the teaching as implemented resulted in a communicative approach by teachers that was broadly consistent with that built into the design of the teaching sequence.

Acknowledgements

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APPENDIX 2: Example of a question used to assess pupils' understanding of modelling change

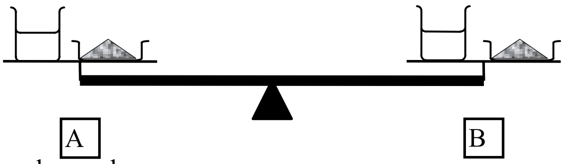
Space for student responses was given in the original

Dissolving

Sonia, Lisa and Hadia are weighing sugar and water.

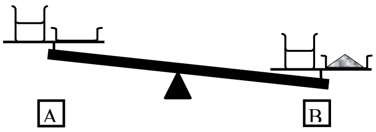
The balance beam is level.

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

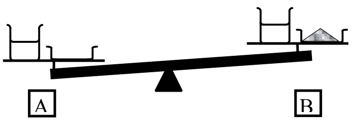


Next, they mix the sugar and water on side A. The sugar can no longer be seen.

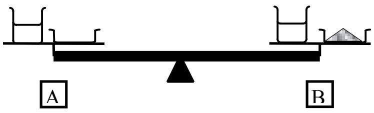
Sonia says: Side A will be **lighter**.



Lisa says: Side A will be **heavier**.



Hadia says: Sides A and B will have **the same mass**.



Discuss this thought experiment with your partner.

Which of the girls do you think is right?

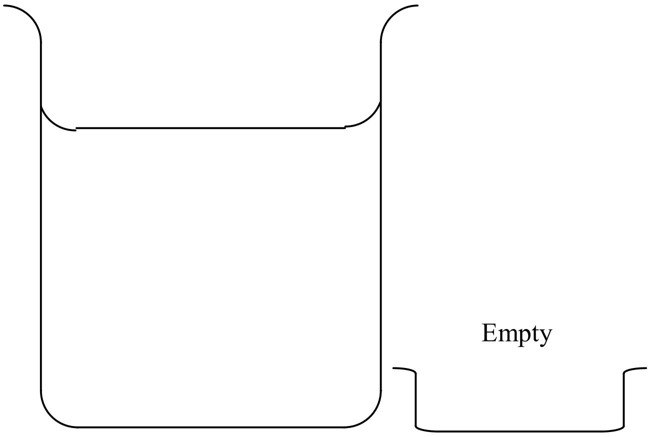
What would you say to convince the other two girls that your answer is correct? Give as much detail as you can!

Imagine that you can see inside the liquid on each side of the balance.

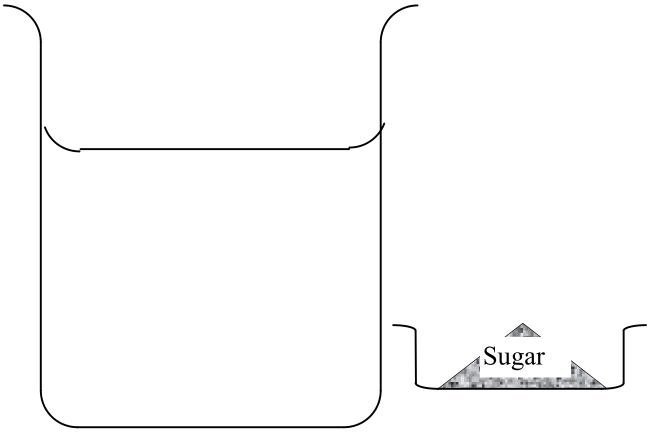
Fill in the diagrams below to show what the liquid is like.

Write some notes to help us to understand your diagram. Explain any differences between the diagrams as fully as you can.

A: the sugar and water are mixed



B: the water is on its own



APPENDIX 3: Questions used to assess pupils' understanding of plant nutrition
Space for student responses was provided in the original.

A plant factory

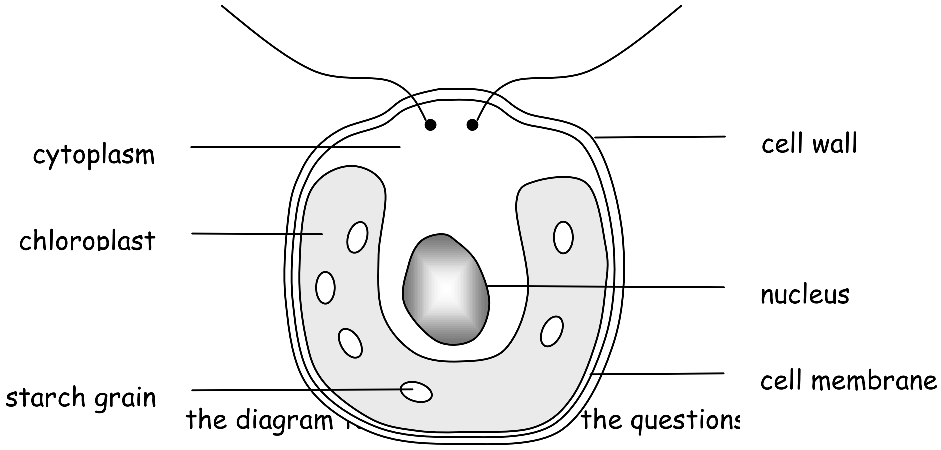
Some people think a plant is a bit like a factory.

1. In the space below explain in what ways you think a plant might be a bit like a factory. (Use a diagram or a cartoon to explain your ideas if this is easier.)
2. If you are thinking of the plant as a factory, which is the most important part?

Explain why you think this.

A pond organism

The diagram below shows a single-celled organism called Chlamydomonas. It lives in pond water.



Use the diagram the questions

(a) Chlamydomonas makes a sugar called glucose. Explain how Chlamydomonas would make the glucose it needs.

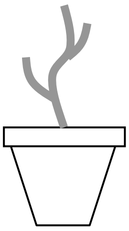
(b) Chlamydomonas produces starch grains from glucose.

(i) Suggest what will happen to the number of starch grains in the cell if Chlamydomonas is kept in the dark.

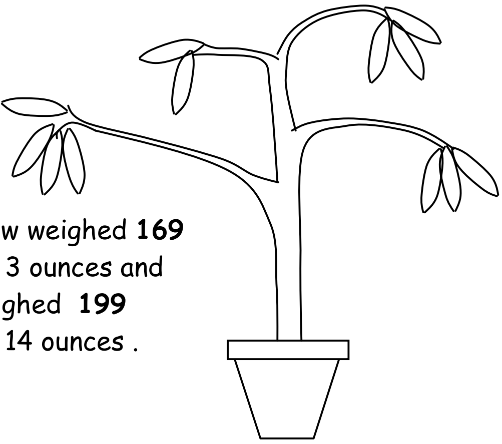
(ii) Explain your answer.

Van Helmont was a Dutch scientist who lived in the 17th century. He did not know about photosynthesis or about chemical elements. Van Helmont carried out an experiment to try and find out what plants are made of.

Here is what he did:



1. He planted a willow tree weighing **5** pounds in **200** pounds of soil.
2. For 5 years he added only rain water
3. The tree now weighed **169** pounds and 3 ounces and the soil weighed **199** pounds and 14 ounces .



From the results of his experiment Van Helmont concluded that; "therefore 164 pounds of wood, barks and roots arose out of water only." This puzzled Van Helmont.

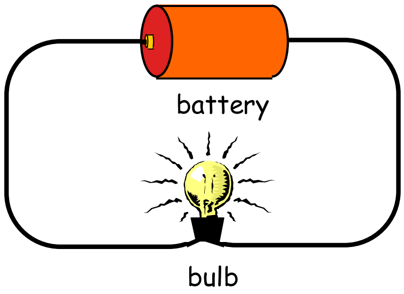
Use your knowledge of plant growth to explain where the mass came from that made up '164 pounds of wood, bark and roots'.

APPENDIX 4: Questions used to assess pupils' understanding of electric circuits

Space for student responses was provided in the original

The following 2 questions were used in the pre-test:

Bulb Light



This is a very simple electric circuit.

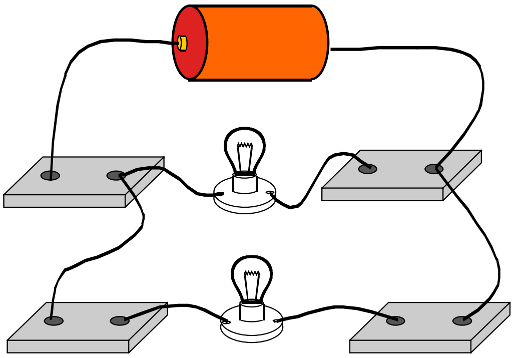
1. Explain in as much detail as you can (thinking about both battery and bulb) <u>why</u> you think the bulb lights up.

2. a) How could you change the circuit to make the bulb brighter?

   b) <u>Explain</u> why this would work.

3. If the circuit is left, <u>why</u> will the battery go FLAT eventually?

Open and Close
Emma wants to make bulb 1 light (and bulb 2 stay off). Which switches does she need to close?

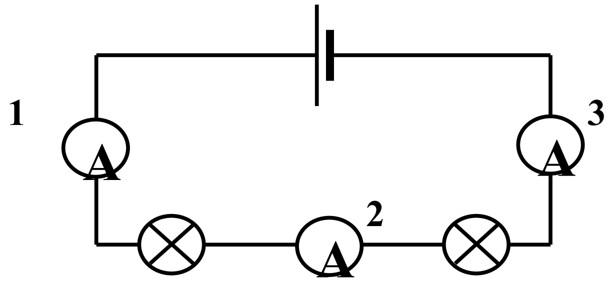


James wants to make bulb 2 light (and bulb 1 stay off). Which switches does he need to close?

Explain why you have chosen these switches.

The following 6 questions were used in the post-test:

Circuit question 1



In this circuit the ammeter at position 1 reads 0.3 Amps.

Predict the value of the current at positions 2 and 3.

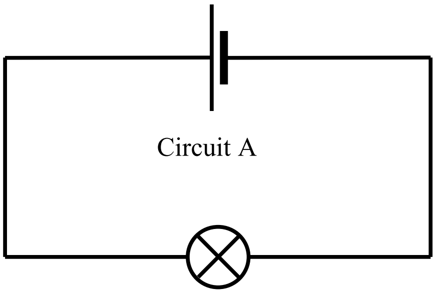
A.	0 Amps
B.	0.15 Amps
C.	0.3 Amps
D.	0.6 Amps

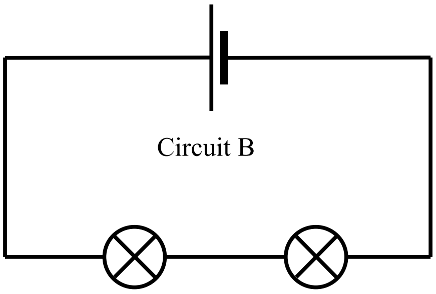
Current at ammeter 2 = ……………………….

Current at ammeter 3 = ……………………….

Explain why you have predicted these values

Circuit question 2





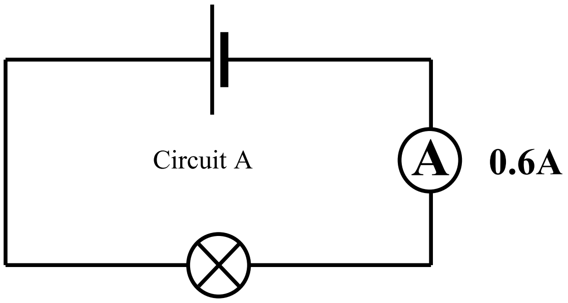
In circuit A the brightness of the bulb is normal.

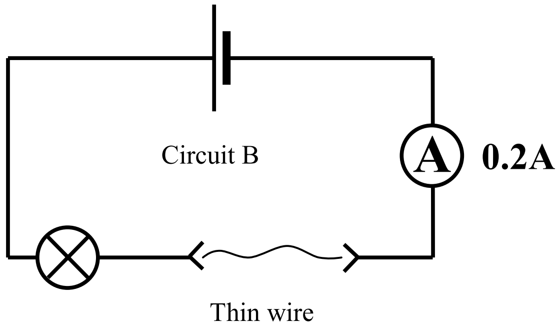
The bulbs in circuit B are:

E. Both dim
F. One normal, one dim
G. Both normal
H. One normal, one off

Explain your answer

Circuit question 3





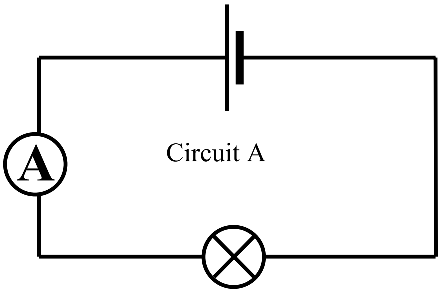
In circuit B there is a thin piece of wire. The thin wire forms part of the circuit.

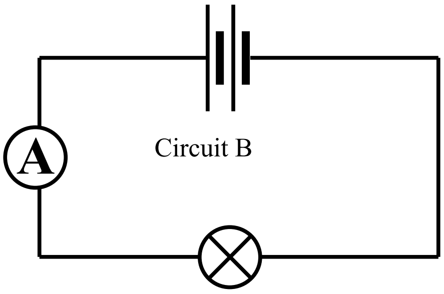
Explain why the current is smaller is in circuit B

What will happen to the brightness of the bulb?

Explain your answer

Circuit question 4





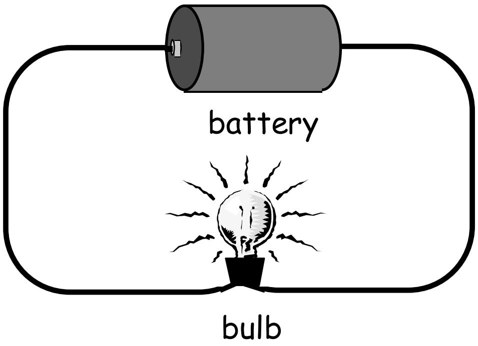
The bulb in circuit A is normal.

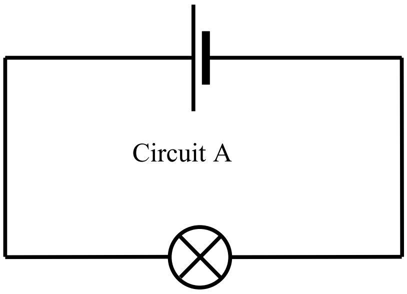
The bulb in circuit B is

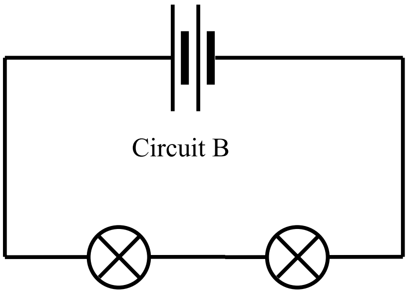
A. Dim
B. Normal
C. Bright
D. Off

Explain your answer

Circuit question 5







What can you say about the brightness of the bulbs in circuits A and B?

E. The bulb in A is normal; the bulbs in B are dim

F. The bulb in A is normal; the bulbs in B are normal

G. The bulb in A is normal; the bulbs in B are bright

H. The bulb in A is normal; the bulbs in B are off

The correct prediction is:

Explain your answer in as much detail as you can

Circuit question 6

This is a very simple electric circuit.

1. Explain in as much detail as you can (thinking about both battery and bulb) <u>why</u> you think the bulb lights up.

2. a) How could you change the circuit to make the bulb brighter?

   b) Explain why this would work.

3. If the circuit is left, why will the battery go FLAT eventually?