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Concept substitution: A teaching strategy for helping students disentangle related physics concepts

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To be effective, physics teachers need both content knowledge and pedagogical content knowledge, which includes knowledge of student conceptions and effective teaching strategies. Although much information is available on student conceptual and reasoning difficulties in physics, much less information is available on how to remedy such difficulties. In this paper I describe a teaching strategy, concept substitution, which is useful when student difficulties arise from a failure to distinguish distinct but related physics concepts. By using the topic of electric circuits as the context, I show how this strategy enables the teacher to identify and build on students' correct intuition, while enabling students to distinguish among related concepts. I also illustrate the complexity of the conceptual change process, including the presence of intermediate conceptions while the process is taking place.
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I. INTRODUCTION

Over the past three decades much effort has been devoted to identifying students' alternative conceptions in physics.[1] A number of alternative student conceptions appear across a wide variety of cultures, countries, and ages.

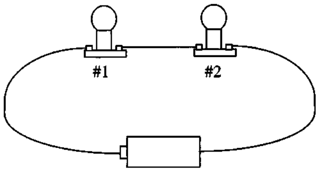
It is important for physics teachers to be aware of these student conceptions. However, a knowledge of alternative conceptions is not enough to ensure improved student learning. Physics teachers also need access to a range of effective instructional strategies to help students undergo a process of conceptual change from the unscientific conceptions they might hold to acceptable scientific concepts.[2] Such strategies form part of what Shulman[3] calls ''pedagogical content knowledge.'' An important feature of pedagogical content knowledge is that it is topic-specific. It includes knowledge of the most useful ways of representing the central ideas in a topic, powerful analogies and examples, common alternative conceptions, and teaching strategies that are effective in helping students reorganize their understanding. According to Shulman, pedagogical content knowledge extends beyond subject matter per se to include ''subject matter knowledge for teaching.'' It is ''the particular form of content knowledge that embodies the aspects of content most germane to its teachability.'' Although secondary and college teachers are expected to achieve a high level of subject matter knowledge, usually by means of formal courses, and secondary teachers are expected to learn about pedagogy, neither secondary nor college teachers usually have a chance to acquire pedagogical content knowledge in a systematic way.

The fact that much physics instruction is not as effective as it should be, as evidenced by research which shows that students often have misconceptions after instruction,[4] indicates that physics instructors need more pedagogical content knowledge. In particular, we need to know both what unscientific conceptions our students hold and what to do about them. To know what alternative student conceptions we should anticipate, research results need to be synthesized and made accessible to teachers. Grayson *et al.*[5] have developed a framework for identifying and categorizing students' conceptual and reasoning difficulties that can help with this synthesis. Other researchers have summarized students' thinking in particular domains. Minstrell[6] has compiled a very useful, comprehensive list of student thinking that differs from scientific explanations in a number of domains.

To know what to do about students' unscientific conceptions, we need to understand how they arise. Various authors have argued that certain alternative conceptions parallel the historical development of scientific concepts.[7] Alternative conceptions also may arise as a result of what diSessa[8] calls ''phenomenological primitives,'' or p-prims, which are, ''relatively minimal abstractions of simple common phenomena'' and ''self-contained explanations for what they [physics-naive students] see.'' In some cases, the teaching approach may reinforce students' p-prims. For example, many students think that if an image of an object is formed on a screen by a converging lens and half the lens is covered, then half of the image will disappear.[9] This misconception may arise from a p-prim like, ''if there is less lens available for light to pass through, then there will be less appearing on the screen.'' The ''less'' may be interpreted by students to mean less of the image, rather than less light (lower intensity). This idea may be reinforced by the standard way in which students are taught to locate the image, namely by drawing two (or three) special rays. When students are required to draw ray diagrams in which rays pass through all parts of the lens, this misconception may largely disappear.[10]

Alternative conceptions also may arise because students

A. For the circuit shown below, predict how bright you think bulb #1 will be compared to bulb #2. Explain how you get your answer.



B. How do the brightnesses of bulbs #1 and #2 in the circuit above compare to the brightness of the bulb A in the circuit below? Explain how you get your answer.

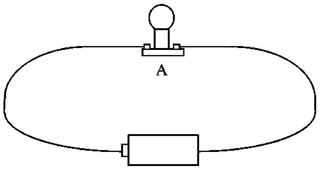


Fig. 1. Pretest given to test for the presence of the ideas that current is used up and a battery is a constant current source.

confuse related but distinct physics concepts. Brown and Clement give examples of such concept differentiation problems in mechanics.[11] In some cases, students hold cluster concepts[12] that are general and vague. For example, students may talk about ''electricity,'' a word that for them has elements of current, voltage, energy, and power all muddled together. In such cases, an effective teaching strategy needs to help students disentangle the related concepts and ascribe scientifically correct meanings to each concept. In the process, the strategy should build on correct student intuitions while remediating incorrect reasoning or conceptual difficulties. In this paper I shall describe one such teaching strategy which I call ''concept substitution.''

II. METHOD

The research described in this paper was conducted with students in the Science Foundation Programme at the University of Natal. This program was designed to help academically talented but disadvantaged black students acquire sufficient skills and knowledge to succeed in science or science-related degrees.[13] It is a one year predegree program for students who have completed high school, but who are not yet ready to begin normal degree studies. The student responses to pretests, assignments, and tests presented in this paper were all part of the normal teaching sequence in the physics component of the program.[14] The exercises and test questions were taken from *Physics by Inquiry*.[15] When reading the students' responses, it is useful to bear in mind that English is their second or third language.

In Sec. III I shall illustrate how the instructional strategy of concept substitution was used to address two of the most prevalent conceptual difficulties in electric circuits, namely, the belief that current is used up in a circuit and that a battery supplies a fixed amount of current, regardless of what is in the circuit.[16] Only the aspects of the teaching sequence and test questions relevant to these two ideas will be presented.

III. RESULTS

A. Initial identification of student conceptions

At the beginning of the first lecture on electricity, the students were asked to write their predictions about the situations shown in Fig. 1. The purpose of this pretest was to see whether students thought that current is used up in a circuit and that a battery is a source of constant current. (In all the pretests the students were told to assume that the bulbs and batteries were identical.) About 30% (11 of 35) of the students thought that bulb No. 1 would be brighter than bulb No. 2, because current is used in bulb No. 1 so less current is available to light bulb No. 2. The other students thought that the two bulbs would be the same brightness, but not necessarily for the right reason. As discussed in Sec. III B, students may have correct ideas, but do not necessarily know which physics concepts to associate with their ideas. The following quotes illustrate this problem. ''The brightness of bulb No. 1 will be the same as that of bulb No. 2 because these bulbs are connected in a series arrangement and the voltage passed through each bulb is the same because it's coming from one source for both bulbs.'' ''Bulb No. 1 will have the same brightness as bulb No. 2. This is because both bulbs are supplied by one battery, and they both (bulb) share the same charges.''

In response to Question 1(b), 20% of the class thought bulb A would have the same brightness as either bulb No. 1 (if they thought bulbs Nos. 1 and 2 would be different) or the same brightness as bulbs Nos. 1 and 2 (if they thought they would be the same), because these students believed that the battery supplies a fixed amount of current, regardless of what is in the circuit.

The other 28 students correctly stated that bulb A will be brighter than bulbs Nos. 1 and 2, but not necessarily for the right reason. In particular, 16 of 35 students indicated in their answers that the battery supplied the same amount of current to both circuits, as illustrated by the typical response: ''The brightness of bulbs in the circuit above will differ from that of bulb A. Bulb A will be brighter than the two bulbs above. This will be because all the current present lights only one bulb, while above the same current has to be divided into two bulbs.''

The responses to the pretest indicate that a significant fraction of the class held the incorrect ideas identified in the literature that current is used up in a circuit and that the battery supplies a fixed amount of current. However, the responses to the pretest also showed that in some of the ''wrong'' answers, there were some right ideas, as illustrated by the following response to Question 1(a): ''Bulb one will be brighter than bulb two, because they are connected in series and the direction of current flow is from positive to negative. When energy reach[es] bulb one it will be used and not as much energy will reach bulb two, so bulb two will be dimmer.''

This student correctly writes that some energy is ''used'' (converted, strictly speaking), but is incorrect in thinking that this use will affect the brightness of the other bulb. As I will discuss, such correct intuitions can be turned into useful building blocks to construct students' scientifically acceptable concepts. The seed of a correct idea could also be identified in the responses to Question 1(b), as evidenced by the fact that even though a fifth of the class thought the bulbs in series would be equal in brightness to the single bulb, several of these students had a sense that something must be different. This sense is suggested by the following response: ‘‘The two bulbs will be bright as equal to A because the two are connected in series. They were to be a bit dimmer than bulb A if they were connected in parallel. The only problem is that the battery for the two bulbs connected in series will only last a shorter time than A’s.’’

Although this response is not correct, the correct idea that putting more bulbs in the circuit must somehow make a difference is evident. This response is an example of how students can give the wrong answer but have some right ideas. Conversely, students can give the right answer for the wrong reason (which is a reason why multiple choice questions can be problematic).

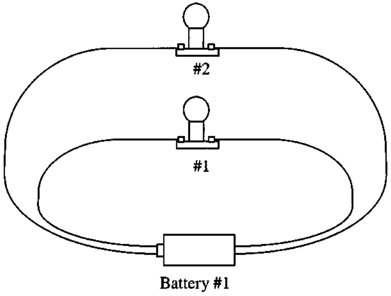
B. First remediation sequence

After the students completed their written predictions, a circuit was shown consisting of a battery in series with three bulbs, with the switch left open. Students were asked to predict orally how the brightnesses of the bulbs would compare with each other when the switch was closed and to justify their predictions. A very lively debate ensued. As expected, a significant fraction of the class argued that the bulb closest to the end of the battery from which they thought the current flowed would be brightest, and the other bulbs would be less and less bright because current would be used up as it passed through successive bulbs. The circuit was then closed and the students saw that the bulbs were equally bright.

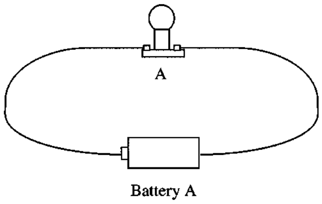
The instructional strategy up to this point resembles what Champagne *et al.*[17] call ‘‘ideational confrontation.’’ Students predicted what they thought would happen and then observed a discrepant event. However, if instruction were to stop here, there is a risk that students would not actually undergo conceptual change because they would not know why their predictions were wrong. After all, batteries go flat after a while, so surely current must be used up! Under such conditions it is possible for students to appear to accept the new idea for a time but then revert back to their previous idea some time later.[18] To avoid this possibility it is important to help students understand why there is a difference between their intuitive ideas and what they observed.

At this point I told the students that they were *correct* to say that something is ‘‘used up,’’ but that ‘‘something’’ is chemical energy, which gets converted to other forms of energy. That is why batteries go flat. By contrast, current just goes round and round the circuit.[19] This teaching strategy of building on correct student intuitions, but substituting the name of the appropriate physics concept for an inappropriate one is what I call concept substitution.[20] Concept substitution involves creating a situation in which it is likely that students will associate a correct intuitive idea with an inappropriate physics concept. When this happens, the instructor reinforces the students’ correct idea, but assigns it another label. In other words, the instructor substitutes the name of the concept with which the students’ idea can be correctly associated for the one used by the students. Some physicists may take exception to introducing a new concept without a careful lead-in. However, the research described in this paper suggests that this disadvantage may be outweighed by the advantage of providing students with a concept early on in the teaching sequence with which they can associate their intuitive ideas, in contrast to expecting them to relinquish their intuitions. In the process, the concept for which it was substituted (current in this case) can be freed of some of the conceptual baggage that students load onto it. Furthermore, when the newly substituted concept is formally developed at a later stage, students already have some feeling for it.

A. For the circuit shown below, predict how bright you think bulb #1 will be compared to bulb #2. Explain how you get your answer.



B. How do the brightnesses of bulbs #1 and #2 in the circuit above compare to the brightness of the bulb A in the circuit below? Explain how you get your answer.



C. How does the amount of current through the *battery #1* compare to the current through *battery A*? Explain.

Fig. 2. Pretest to further test for the presence of the idea that a battery is a constant current source.

To confront the other incorrect idea, namely that the battery supplies a constant amount of current regardless of what is in the circuit, three circuits were set up in the front of the room: one with a battery and one bulb, one with two bulbs in series, and one with three bulbs in series. The switches were left open. Students were asked to make verbal predictions of the brightnesses of the bulbs in the different circuits, assuming that the brightness of the bulb indicates the amount of current flowing through it.[21] After some debate and discussion, the switches were closed, and students observed that the more bulbs there are in the circuit, the dimmer they are, implying that the battery supplies different amounts of current depending upon what is in the circuit. There was not enough time in the period, however, to use concept substitution again to help students begin to distinguish between the current supplied by the battery, which is not constant in every circuit, and the quantity that is constant (voltage). Before the next lecture students did a two and half hour laboratory session on series and parallel combinations of bulbs using ammeters to measure currents and nichrome wires of different lengths instead of bulbs. The concept of resistance was introduced, and students determined experimentally that current is inversely related to resistance.

C. Second identification of student conceptions

At the beginning of the next lecture, students wrote responses to questions in Fig. 2. All but five of the students realized that both bulbs in Fig. 2(a) would be the same brightness. In response to Question 2(b), 25 of the 35 students incorrectly said that bulb A would be brighter than bulbs Nos. 1 or 2. Once again, the notion that a battery supplies a fixed amount of current was evident in the students’ responses.

In response to Question 2(c), 26 of the 35 students said the current flowing through the two batteries would be the same, regardless of the number of bulbs in the circuit. Although at the end of the previous lecture students had seen that the brightness of bulbs in series differs when there are differing numbers of bulbs in the circuit (we used brightness as an indication of the current), this demonstration and the discussion of the results was not enough to shake students' belief that the battery is a constant current source. This belief seems to be based on the students' understanding of the ''sameness'' of the batteries, as illustrated by the following quote: ''The current through battery No. 1 and A will be the same because it's the same battery therefore they are giving the same amount of current.''

However, as in the previous lecture, several students felt that something must be different about the two circuits. In the following response, the student uses the only other electrical concept she has encountered in the course so far, energy, to explain the difference: ''The amount of current is the same because there is one battery in each circuit therefore it is the energy that will differ but not the electric current.''

As with the first pretest, correct ideas could be identified in incorrect responses. In the following quotes students demonstrated correct thinking when they said that the battery that supplies two bulbs will go flat first, even though they were not correct in saying that the amount of current supplied by both batteries was the same. ''Current through battery No. 1 is the same as the current through battery A. The only difference is that battery No. 1 will go flat quicker than battery A because it supplies current to two bulbs.'' ''The amount of current in battery No. 1 and battery A is the same, the chemical energy of battery A will last longer than that of battery No. 1 because battery No. 1 is supplying current to two bulbs, whereas battery A to a single bulb.''

Although many students still believed that the batteries supplied the same amount of current, these quotes show that students were beginning to distinguish current and energy as two different concepts. There also was evidence in some of the responses that the concept substitution employed in the last lecture helped students accept the idea that the ''something'' that gets ''used up'' in a circuit is not current but energy (even if the overall responses were not correct): ''The amount of current through battery No. 1 is the same as the amount of current through battery No. 2 because there is no current used up by bulbs. So the current send[t] will be equal to the current received.'' ''The brightness also will be the same because above bulbs [Nos. 1 and 2] were parallel to each other and to the battery. Current will never be used up. Current will be the same. The difference might be time of light of bulbs Nos. 1, 2, and A. Bulb A would light long time because there is 1 bulb to 1 battery.''

An interesting aspect of these quotes is that it seems as if the students are using their new knowledge that current is not used up as a justification for their belief that the current in the two batteries must be the same. If teaching had ended at this point this misconception might have been reinforced rather than remediated by the teaching strategy.

Sometimes students seem to be in a transition state between their old conception and the new scientific concept. The two following quotes give an illustration. The first quote is a student's response to Fig. 2(b) on the second pretest, while the second quote is his response to Fig. 1(b) on the first pretest. ''Bulb A will have more brightness than Nos. 1 and 2 because all the energy that the battery sends out is used all by bulb A whereas the energy from the battery No. 1 in diagram above is shared by both bulbs, Nos. 1 and 2.'' ''Bulb A will be more brighter than bulbs Nos. 1 and 2, because all of the current goes to one bulb, A whereas in the above [series circuit] the current is shared amongst two bulbs, Nos. 1 and 2.''

In the second pretest the student has replaced ''current'' with ''energy'' as the quantity that is used, but has not yet clearly separated out the concepts of energy and current. Although he uses the word ''energy,'' he still associated certain aspects of current with the word. This association is an example of an intermediate conception.[22] The student has moved away from his original conception, but has not yet moved all the way to the scientific concept. As shown in Ref. 23 while moving from an alternative conception to scientific concept, students do not necessarily undergo a discrete change from one concept to another. Students' conceptions are not like two-state systems, which are either right or wrong. There are all sorts of intermediate conceptions along the path to conceptual change. Moreover, students may move back and forth between the ''old'' and ''new'' conceptions depending on the context, remaining for some time in a kind of metastable conceptual state. It may take multiple passes at confronting and resolving an alternative conception before a student finally relinquishes the conception and can be thought of as being in a stable conceptual state. For this reason, one-shot efforts at conceptual change may not be effective.

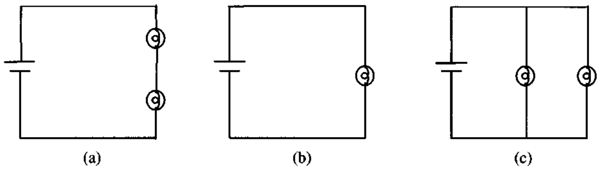
D. Second remediation strategy

As in the previous lecture, students handed in their predictions and then looked at two circuits with the switches open. One circuit had two bulbs in parallel with a battery and the other consisted of a single bulb and a battery. Students debated their predictions in class. When the switches were closed, students saw that the bulbs were all the same brightness, demonstrating that branches of a parallel circuit are essentially independent (when internal resistance can be ignored). Thus each bulb in each branch glows with the same brightness as the bulb in a single bulb circuit. It can then be deduced that the current through the battery in the circuit with two bulbs in parallel must be twice that in a single branch circuit.

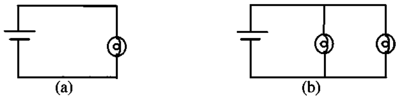
At this point concept substitution again was used. The students were told that they were *right* to say that something about the batteries is the same, but the ''something'' is called voltage. The same kind of batteries provide the same voltage. The battery is not a source of constant current. Current depends on what is in a circuit. Adding bulbs in series provides more of an obstacle to flow, so there will be less current; adding bulbs in parallel provides more paths so more current can flow.

Students were shown two more demonstrations to reinforce this concept. In the first demonstration, they saw a parallel circuit in which one branch had one bulb and the other branch had two bulbs. Students made oral predictions of the brightness of the bulbs and the current through the batteries. In the second demonstration they saw a parallel circuit consisting of one branch with 30 cm of nichrome wire and one branch with 15 cm of nichrome wire. An ammeter was inserted in each branch and the current was measured. The current through the battery was also measured. From these demonstrations it was concluded that current depends on the resistance in a branch (or path) and the number of

A. Place the following circuits in order according to the amount current through the battery. Explain your reasoning.



B. Consider the following dispute between two students.



Student #1: The current through the battery in each circuit is the same. In circuit (b) the current from the battery is divided between the two bulbs - so each bulb has half the current through it that the bulb in circuit (a) has through it.

Student #2: We know the current through each of the bulbs in circuit (b) is the same as through the bulb in circuit (a). That's because the bulbs are all about the same brightness - and bulbs that are equally bright have the same current through them. So the flow through the battery in circuit (b) is more than that through the battery in circuit (a).

Do you agree with Student #1 or Student #2? Explain.

Fig. 3. Assignment given six days after instruction designed to test for the presence of the idea that a battery is a constant current source.

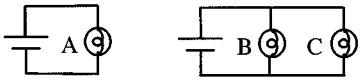
paths. A summary of the teaching sequence for the rest of the section on electricity is given in the Appendix.

E. Time-delayed effects of the instructional strategies

Six days after the class period described in Sec. III D, students handed in their answers to the homework questions in Fig. 3. In response to Question 3(a), only 9% of the students (3/34) incorrectly said the current was the same in all three circuits. In response to Question 3(b), these three students and one other student, 4/34 in all, agreed with student No. 1's incorrect reasoning.

Twenty days after instruction students handed in responses to the questions in Figs. 4 and 5. A student who thought that the battery supplied a fixed amount of current should agree with student No. 1 in Fig. 4. Only 4/34 incorrectly said student No. 1 is right; the rest gave the correct answer. [It is interesting that three of these four students were different from those who gave the incorrect answer in Question 3(b).] An indication of the degree of understanding most students seemed to have acquired by this stage is given by the following responses: “Student No. 1 is not correct as the bulbs A, B and C will be equally bright since the current through the battery depends on what is in the circuit thus the circuit with bulb B and C will [have] twice current as circuit with bulb A and thus bulb B and C share the current which then each get current equal to current through bulb A thus they light with the same brightness.” “Student No. 1 is incorrect because we can’t say something in the circuit gets all the current because there is no fixed amount of current in the first place. To correct No. 1 I would say that A=B=C because since A and B and C have the same resistance and B and C are connected directly to the battery, they demand more current from the battery to keep them burning like bulb A (depending on their resistance).”

In this exercise, three students give predictions and explanations for the relative brightness of bulbs *A*, *B* and *C*. Say whether each student's reasoning is correct or not. If it is incorrect, say why.



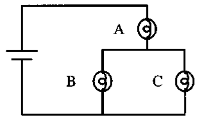
Student #1: B and C will be dimmer than A. Bulb A gets all of the current from the battery but B and C have to share it.

Student #2: A, B and C will all be equally bright. They each have the same voltage across them.

Student #3: A, B and C will all be equally bright. Each has the same resistance, and each is connected directly across the battery, so each bulb has the same amount of current through it. So they are equally bright.

Fig. 4. Assignment given 20 days after instruction designed to test whether students think the battery is a constant current source.

In this exercise, four students give explanations for the observation that the identical bulbs *B* and *C* are dimmer than *A*. Say whether each student's reasoning is correct or not. If it is not correct, explain why.



Student #1: B and C are equally bright but dimmer than A. B and C have to share the current whereas A gets all of it. Therefore A is brighter than B or C.

Student #2: Bulb A has more resistance than the B-and-C network so bulb A has more voltage across it. Therefore A is brighter than B or C.

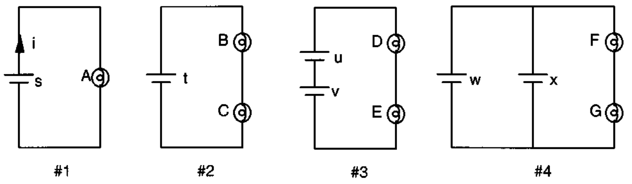
Student #3: Bulb *A* uses up most of the current so less is left for *B* and C. *A* is therefore brighter than *B* or *C*.

Student #4: After bulb A, the voltage divides into two paths with the result that B and C each get less voltage than A. Therefore A is brighter than B or C.

Fig. 5. Assignment given 20 days after instruction designed to test for the presence of the idea that current is used up in a circuit.

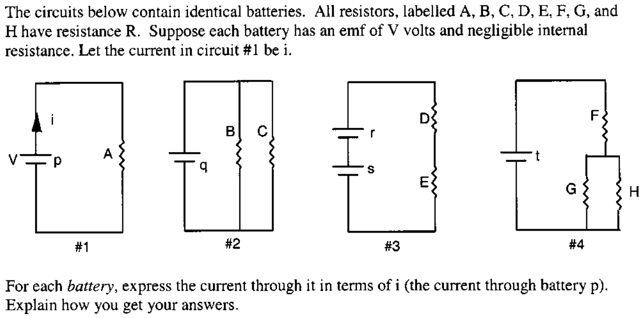
Any student who still thought that current gets used up in a circuit should agree with student No. 3 in Fig. 5. Only 18% of the class (6/34) agreed with student No. 3 and thought that current gets used up; the rest disagreed (correct). Of those who disagreed, 70% used the words “current is never used up” in their responses. The extent to which students seemed to have incorporated the notion that current does not get used up into their understanding is suggested by the following responses in which students were able to modify and elaborate the answers of the “student” in the question. The first quote suggests that the use of concept substitution helped him to distinguish between current and energy. The quality of these explanations is particularly impressive considering the fact that for these students English is their second or third language. “Student No. 3 is incorrect because current isn’t used up, energy is. The current through A will be the same as that in B and C except that before B and C current divides. Some of it goes to C whilst some of it goes to B.” “Student

The circuits below contain identical bulbs and batteries.



Suppose that the current through Battery s in circuit #1 is i. Write an expression for the current through each of the other batteries (t, u, v, w, and x) in terms of i. Explain how you get your answers.

Fig. 6. Test question given 25 days after instruction designed to test for the presence of the idea that a battery is a constant current source.



The circuits below contain identical batteries. All resistors, labelled A, B, C, D, E, F, G, and H have resistance R. Suppose each battery has an emf of V volts and negligible internal resistance. Let the current in circuit #1 be i.

For each *battery*, express the current through it in terms of i (the current through battery p). Explain how you get your answers.

Fig. 7. Final examination question given 111 days after instruction designed to test for the idea that a battery is a constant current source.

3 is incorrect because current is never used up but the current which was gotten by A is now divided between B and C thus they will have less brightness than A."

Twenty-five days after instruction students were given a test that included the question in Fig. 6. 26% of the students (9/35) thought that the current through batteries *s* and *t* would be the same, of whom only two had given answers to the questions in Figs. 3, 4, or 5 that indicated that they thought that batteries supplied a fixed amount of current. Whether it was the format of the question, the stress of a test situation, or both that led these students to revert to constant current notions [revealed in Question 2(c)] is not known. However, these results show that conceptual change may be less stable than instructors may think.

At the end of the semester (111 days after instruction) students wrote the final physics examination, which included the question in Fig. 7. Only two students thought that the current would be the same in all cases where the number of batteries was the same.

IV. DISCUSSION

Many researchers have drawn attention to the need to identify and address students' incorrect conceptions.[24] However, it also is important to identify and exploit students' correct conceptions and intuitions.[25] I have given several illustrations of student responses that contained correct ideas, even though the overall response may not have been correct. There are a number of ways of characterizing these ideas. For example, they may be thought of as naive conceptions or intuitions. Some of the students' responses can be explained in terms of diSessa's p-prims.[26] For example, the misconception that batteries of the same type always supply the same amount of current may stem from a p-prim that might be stated as "the same kind of objects behave in the same way." In the case of batteries, an implication of such a p-prim is that "the same kind of batteries supply the same amount of electricity." For the novice physics student the problem is not with the p-prim, because this assertion is reasonable. The problem lies in deciding how to map the everyday term "electricity" onto the appropriate physics term. For students who have not yet learned basic electrical concepts, electricity could mean current, voltage, energy, power, or even some combination of these concepts. The challenge to instructors is to use students' correct ideas, whether they are conceived of as p-prims or intuitions, as a resource[27] to help students develop a sound understanding of the physics concepts.

Concept substitution is one teaching strategy for exploiting students' correct ideas in a particular context. It involves identifying a correct student intuition that has been linked to an inappropriate physics concept and helping students associate their intuitive idea with the appropriate concept. There are several possible advantages to using this strategy. First, students may find it encouraging to hear that they have some correct ideas. Second, because students are not asked to give up their intuitive ideas, they may feel that physics makes more sense to them than often happens when traditional teaching approaches are used. Third, when the concept that has been substituted by the instructor is encountered later on in the course, students already have some intuition about that concept. Fourth, the approach encourages students to distinguish among related concepts that may otherwise remain undifferentiated in their minds. As a result, certain apparent misconceptions may be remediated.

I have shown that the percentage of students in a Foundation Physics course who held two prevalent misconceptions, namely the notion that current is used up in a circuit and the notion that a battery supplies a fixed amount of current regardless of what is in the circuit, was substantially reduced during the course. I suggest that this reduction was, at least in part, a result of using concept substitution to help students distinguish between current and energy and between current and voltage. By distinguishing between current and energy, students were able to hold onto their correct intuition that something gets used up because batteries go flat, but separate it from the concept of current. By distinguishing between current and voltage, students were able to hold onto their correct intuition that the batteries are the same in some way, but do not supply the same amount of current. It is likely that both applications of concept substitution also helped students develop an understanding of current as something that flows unattenuated through a circuit and that depends on the components and configuration of the circuit.

The sound understanding of the targeted physics concepts that most of the students were able to demonstrate strongly suggests that the new ideas made sense to them. The process of sense-making was almost certainly aided by allowing students to retain their correct intuitions and build on them rather than insisting that these ideas be cast aside. There also is an affective dimension to the process—when students are told that their ideas are right, it probably boosts their confidence. Given the widespread perception that physics is difficult, this point is not trivial.

There are indications that concept substitution also has been a useful teaching approach in other areas of physics. In mechanics many students think that if an object is thrown into the air, it will have a "force of the thrower" acting on it even when it is in mid air.[28] Concept substitution has been used to help students associate their correct intuitive idea that the thrower imparts something that travels with the object with the concept of momentum rather than force. In the process the apparent misconception that a "force of the thrower" acts on a moving object may largely disappear.[29] In the area of heat and temperature, students know that objects made of different materials feel different, even though they may have been in the same environment for a long time. Introducing the concept of rate of heat transfer allows students to relate the sensation of feeling different to this new concept, and separate out the concept of temperature. As a result, most students can make sense of the fact that objects can be at the same temperature and yet feel different to the touch. They also learn that temperature cannot be reliably determined by feel.[30]

Concept substitution, however, is no magic pill. As I have shown, conceptual change is not a quick or simple process. Students may spend some time in an unstable conceptual state, oscillating between their original conception and the target scientific concept. For example, in response to Question 3(b), one student wrote: "I agree with student No. 2 because when bulbs are connected in parallel they each receive current from the battery as if the others are not present, therefore the two bulbs in circuit (b) draw more current than the bulb in circuit (a)." However, in her response to Question 4 2 weeks later, she incorrectly said that student No. 1 was correct. Students also may combine elements of both concepts into a sort of intermediate conception.[31] As a result, students may need to confront their old conception and apply the new concept several times and in a variety of contexts before an instructor can be reasonably confident that the students have really embraced the scientific concept and reached a stable conceptual state. Nonetheless, concept substitution seems to provide the conditions proposed in Ref. 32 that are required for conceptual change to occur, namely that the new concept should be intelligible, fruitful, and plausible and should not be a source of dissatisfaction. Concept substitution may be particularly helpful in meeting the fourth requirement, because allowing students to hold onto their intuitive ideas means that there is less likelihood that the target scientific concept will be a source of dissatisfaction to them.

V. IMPLICATIONS

I suggested in Sec. I that physics teachers need more than just content knowledge—they also need pedagogical content knowledge. One component of pedagogical content knowledge is knowledge of likely student difficulties. However, another, perhaps even more important component, is knowledge of how to help students overcome these difficulties. In the physics education research community, much more attention has been devoted to the first kind of pedagogical content knowledge than to the second. There are notable exceptions. Arons made an enormous contribution to our knowledge of how to teach physics effectively,[24] and the curriculum materials developed by the Physics Education Group at the University of Washington[15] have applied and further developed the teaching approaches he advocated. Minstrell[33] also has made significant contributions to our knowledge of effective teaching strategies. A number of curriculum innovations, such as Real-Time Physics,[34] center around effective teaching strategies. However, although these contributions are very valuable, much more effort still needs to go into identifying specific teaching strategies that are shown to be effective in helping students develop the desired conceptual understanding and scientific reasoning skills.

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APPENDIX: SUMMARY OF THE TEACHING SEQUENCE AFTER THE SECOND USE OF CONCEPT SUBSTITUTION

The day number refers to the number of days after the second use of concept substitution.

Day 1: Pretest on how students think current varies in different parts of a series-parallel circuit. Discussion of experiments students conducted in the laboratory related to how current changes according to the resistance in a circuit and the configuration of circuit elements. Introduction to Kirchoff's First Law.

Day 4: Pretest on how students think voltages will compare across bulbs and across batteries in series and parallel circuits. Examples of Kirchoff's first law problems.

Day 6: Laboratory session on measuring voltage across different parts of a circuit, relating voltage and current, voltages in series and parallel.

Day 7: Lecture on voltage, using gravitational analogy. Voltages are the same between any points that are electrically the same. Total voltage determined by the battery. Voltage divides in proportion to resistance.

Day 8: Demonstrations and discussion of effect of unscrewing a bulb in a parallel circuit and in a series-parallel circuit in terms of voltage and resistance. Examples of calculating voltages in series-parallel circuits given resistances using proportional reasoning (no current calculations). Comparison of voltage and current.

Day 11: Introduction of Ohm's law for a linear resistor. Introduction and examples of Kirchoff's second law.

Day 13: Laboratory session on Kirchoff's second law, Ohm's Law and real batteries (effect of internal resistance).

Day 14: Derivation of equivalent resistance for parallel circuits. Discussion of internal resistance. Problems on internal resistance and equivalent resistance.

Day 15: Students work on problems involving Kirchoff's laws, equivalent resistance, internal resistance.

Day 18: Definition of current as rate of flow of charge, voltage as difference in electrical potential energy per unit charge. Introduction to power, power ratings of household appliances, circuit breakers.

Day 20: Students work on more complex problems on equivalent resistance, Kirchoff's laws, power, conversion from electrical to thermal energy.

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[1] H. Pfundt and R. Duit, *Bibliography: Students' Alternative Frameworks and Science Education* (IPN, University of Kiel, Germany, 1998).
[2] P. H. Scott, H. M. Asoko, and R. H. Driver, "Teaching for conceptual change: A review of strategies," in *Research in Physics Learning: Theoretical Issues and Empirical Studies*, edited by R. Duit, F. Goldberg, and H. Niedderer (IPN, Kiel, Germany, 1992), pp. 310–329.
[3] L. S. Shulman, "Those who understand: Knowledge growth in teaching," Educ. Res. **15**(2), 4–14 (1986).
[4] L. C. McDermott, "What we teach and what is learned-Closing the gap," Am. J. Phys. **59**(4), 301–315 (1991).
[5] D. J. Grayson, T. R. Anderson, and L. G. Crossley, "A four-level framework for identifying and classifying student conceptual and reasoning difficulties," Int. J. Sci. Educ. **23**(6), 611–622 (2001).
[6] J. Minstrell, "Facets of students' thinking" ⟨http://depts.washington.edu/huntlab/diagnoser/facetcode.html⟩
[7] I. Galili and A. Hazan, "The influence of an historically oriented course on students' content knowledge in optics evaluated by means of facets-schemes analysis," Am. J. Phys. **68**(7), S3–S15 (2000).
[8] A. A. diSessa, "Phenomenology and the evolution of intuition," in *Mental Models*, edited by D. Gentner and A. L. Stevens (Lawrence Erlbaum, Hillsdale, NJ, 1983), pp. 15–33.

[9] F. Goldberg and L. C. McDermott, ''An investigation of student understanding of the real image formed by a converging lens or concave mirror,'' Am. J. Phys. **55**(2), 108–119 (1987); T. Fetherstonhaugh and D. F. Treagust, ''Students' understanding of light and its properties: Teaching to engender conceptual change,'' Sci. Educ. **76**(6), 653–672 (1992).

[10] D. J. Grayson, ''Many rays are better than two,'' Phys. Teach. **33**(1), 42–44 (1995).

[11] D. Brown and J. Clement, ''Classroom teaching experiments in mechanics,'' in *Research in Physics Learning: Theoretical Issues and Empirical Studies*, edited by R. Duit, F. Goldberg, and H. Niedderer (IPN, Kiel, 1992), pp. 380–397.

[12] H. Niedderer, ''Alternative frameworks of students in mechanics and atomic physics: Methods of research and results,'' in *Proceedings of the Second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics*, edited by J. D. Novak (Cornell University Press, Ithaca, N.Y., 1987), pp. 335–348.

[13] D. J. Grayson, ''A holistic approach to preparing disadvantaged students to succeed in tertiary science studies. Part I: Design of the Science Foundation Programme (SFP),'' Int. J. Sci. Educ. **18**(8), 993–1013 (1996).

[14] D. J. Grayson, ''Foundation physics: A developmental approach to preparing disadvantaged students for mainstream physics,'' in *The Changing Role of Physics Departments in Modern Universities*, Proceedings of International Conference on Undergraduate Physics Education, Part One: Presentations, edited by E. F. Redish and J. S. Rigden (American Institute of Physics, New York, 1997), pp. 583–593.

[15] L. C. McDermott, *Physics by Inquiry* (Wiley, New York, 1996).

[16] L. C. McDermott and P. Shaffer, ''Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding,'' Am. J. Phys. **60**(11), 994–1003 (1992); D. Shipstone, ''Electricity in simple circuits,'' in *Children's Ideas in Science*, edited by R. Driver, E. Guesne, and A. Tiberghien (Open University Press, Milton Keynes, 1985), pp. 33–51; D. M. Shipstone, C. von Rhöneck, W. Jung, C. Kärrqvist, J. J. Dupin, S. Johsua, and P. Licht, ''A study of students' understanding of electricity in five European countries,'' Int. J. Sci. Educ. **10**(3), 303–316 (1988); A. A. Tiberghien, ''Critical review on the research aimed at elucidating the sense that the notions of electric circuits have for students aged 8 to 20 years,'' in *Research on Physics Education*, Proceedings of the First International Workshop, LIRESPT, Université de Paris VII (éditions du CRNS, Paris, France, 1984), pp. 109–123.

[17] A. B. Champagne, R. F. Gunstone, and L. E. Klopfer, ''Instructional consequences of students' knowledge about physical phenomena,'' in *Cognitive Structure and Conceptual Change*, edited by L. H. T. West and A. L. Pines (Academic, Orlando, 1985), pp. 61–90.

[18] R. White, ''Implications of recent research on learning for curriculum and assessment,'' J. Curriculum Studies **24**, 153–164 (1992).

[19] The strategy of separating out the notions of energy and current also has been used successfully by Johsua and Dupin, but they used it in the context of a modeling analogy. See S. Johsua and J. J. Dupin, ''Taking into account student conceptions in instructional strategy: An example in physics,'' Cogn. Instruct. **4**(2), 117–135 (1987).

[20] D. J. Grayson, ''Concept substitution: A strategy for promoting conceptual change,'' in *Improving Teaching and Learning in Science and Mathematics*, edited by D. F. Treagust, R. Duit, and B. J. Fraser (Teachers College Press, New York, 1996), pp. 152–161.

[21] L. C. McDermott and P. Shaffer, ''Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies,'' Am. J. Phys. **60**(11), 1003–1013 (1992).

[22] I use the term ''intermediate conception'' to indicate a conception that may have elements of both an alternative conception and the scientific concept. As such, it would not be regarded as scientifically correct. This use is different from Brown and Clement's intermediate concepts, which they define as, ''stepping stones to the physicist's more abstract and general concepts.'' Their intermediate concepts are correct but less elegant or powerful than scientific concepts.

[23] A. G. Harrison, D. J. Grayson, and D. F. Treagust, ''Investigating a Grade 11 student's evolving conceptions of heat and temperature,'' J. Res. Sci. Teach. **36**(1), 55–87 (1999).

[24] See, for example, A. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990), and Ref. 4.

[25] J. Clement, D. E. Brown, and A. Zietsman, ''Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuitions,'' Int. J. Sci. Educ. **11**, 554–565 (1989); S. Johsua and J. J. Dupin, ''Taking into account student conceptions in instructional strategy: An example in physics,'' Cogn. Instruct. **4**(2), 117–135 (1987); D. Hammer, ''Student resources for learning introductory physics,'' Am. J. Phys. **68**(7), S52–S59 (2000).

[26] A. A. diSessa, ''Phenomenology and the Evolution of Intuition,'' in *Mental Models*, edited by D. Gentner and A. L. Stevens (Lawrence Erlbaum, Hillsdale, N.J., 1983), pp. 15–33.

[27] D. Hammer, in Ref. 25.

[28] J. Clement, ''Students' preconceptions in introductory mechanics,'' Am. J. Phys. **50**(1), 66–71 (1982); I. A. Halloun and D. Hestenes, ''Common sense concepts about motion,'' *ibid.* **53**(11), 1056–1065 (1985).

[29] D. J. Grayson, ''Concept substitution: An instructional strategy for promoting conceptual change,'' Res. Sci. Educ. **24**, 102–111 (1994).

[30] In Ref. 20, pp. 152–161.

[31] For a much more detailed treatment illustrating the complexities of the process of conceptual change, see Ref. 23.

[32] P. Hewson and R. Thorley, ''The conditions of conceptual change in the classroom,'' Int. J. Sci. Educ. **11**(5), 541–553 (1989).

[33] J. Minstrell, ''Teaching science for understanding,'' in *Toward the Thinking Curriculum: Current Cognitive Research*, edited by L. B. Resnick and L. E. Klopfer (ASCD, Alexandria, VA, 1989), pp. 129–149.

[34] D. R. Sokoloff, R. Thornton, and P. Laws, *RealTime Physics* (Wiley, New York, 1999).