Macroscopic phenomena and microscopic processes: Student understanding of transients in direct current electric circuits

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Studies of student understanding of simple electric dc circuits have shown that many of them find it very difficult to apply qualitative reasoning to explain the observed phenomena. It has been suggested that these difficulties may be due to their failure to construct models of microscopic processes that lead to these phenomena. Indeed, in the traditional courses, such models have generally not been emphasized. In the present study, we compared the performance of different groups of university students in answering a questionnaire designed to probe their understanding of the relationship between macroscopic phenomena of transients in a dc circuit and the microscopic processes that can explain these phenomena. One group studied from a traditional text, the second group used a recently developed text that emphasizes models of microscopic processes. We also conducted detailed interviews with some of the students. From an analysis of the performance of these two groups, and also from a comparison with a previous study on Israeli high school students, we found that most of the students whose instructional experiences included an emphasis on the development of models of microscopic processes developed a better understanding of the transient phenomena studied. They applied qualitative considerations in their analyses and were able to develop coherent models to describe their observations. Overall, they demonstrated a superior understanding of the physical phenomena.

I. INTRODUCTION

There is a large body of research literature on student understanding in the area of mechanics and a number of useful diagnostic tests have been developed.[1,2] Such tests, when used as pre- and post-tests in conjunction with instruction, help teachers identify student conceptions and mental models. These usually evolve as a complex combination of everyday experiences and ideas developed through instruction.

Studies in the area of electricity and magnetism are less abundant. However, in recent years physics education researchers have also turned their attention to this area,[3–16] and some diagnostic tests are being developed.[17]

A central argument made by Eylon and Ganiel[13] is that in order for students to be able to reason in qualitative terms about phenomena occurring in electric circuits, they need to develop robust models of microscopic processes which will enable them to understand the underlying processes, leading to the macroscopic phenomena observed. At the time that argument was made, there existed no clear empirical manifestation that would support this assumption.

Recently, a new E&M text has been developed by Chabay and Sherwood.[18] This text emphasizes models of microscopic processes and requires students to explain their reasoning. More and more instructors in US universities are beginning to use the text, opening the possibility of empirically testing the assumptions alluded to above.

We have studied students' conceptual understanding of transients in direct current (dc) electric circuits, drawing on the previous study by Eylon and Ganiel.[13] We find that by developing an understanding of models of microscopic processes for electric phenomena during instruction, students can be led to develop a better understanding of macroscopic phenomena, as argued by Eylon and Ganiel.[13]

We studied two groups of students. One group consisted of engineering students taught from a traditional text,[19] which deals with transients in dc electric circuits in a conventional manner, using mathematical formulations (Ohm's law, RC circuits, etc.). A second group consisted of engineering students taught from a text that emphasizes models of microscopic processes,[18] but also uses standard mathematical analysis with macroscopic variables.

We found that most of the students taught traditionally did not possess any well-defined mental models about concepts and processes related to transient behavior in dc electric circuits. These students did not develop any qualitative understanding, even though they were often able to solve standard quantitative problems by manipulating equations and using memorized formulae. Students in the other group did develop sensible models for transients in dc electric circuits in their minds, and consequently showed a much better qualitative understanding of the phenomena. This was clearly demonstrated by their ability to explain causal relationships for the phenomena posed in the questions.

II. METHOD

Our study consisted of a written questionnaire on transients in dc electric circuits administered to two groups: 90 students in the introductory sequence (calculus based), at The Ohio State University (OSU, hereafter to be referred to as group A), who used a traditional text,[19] and 29 students in the introductory (calculus based) sequence at the University of Michigan-Flint (UM, hereafter referred to as group B),

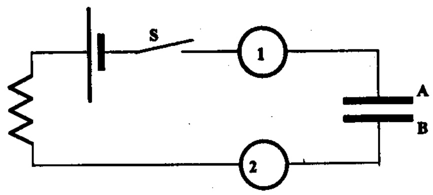

Fig. 1. Circuit 1.

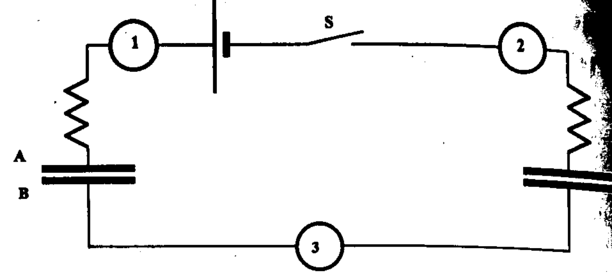

Fig. 2. Circuit 2.

who used a text which emphasizes models of microscopic processes.[18] We also interviewed 20 students and 6 students, respectively, from the same populations. The questionnaire was designed to probe students' qualitative understanding of the transient behavior of electric dc circuits. The reasons for this choice are explained below. The questionnaire enabled us to identify commonalities among a large number of students, while the interviews were instrumental for probing deeper than could be done with the questionnaire.

The students were asked to take no more than an hour to fill out the questionnaire, and to answer individually, in their own words, without referring to a text. The interviews were about an hour long and covered the same problems as contained in the questionnaire. Students were selected for interviews by selecting a uniform mix of A, B, and C students. In all three cases, the questionnaires were administered and the interviews conducted in the last few weeks of their E&M course.

In addition, we compare our results, when possible, to the previous study of Israeli high school students (group HS) by Eylon and Ganiel.[13] The Israeli students completed a written questionnaire almost identical to the one in this study. (There was one additional question added in the present study.)

A. Discussion of the teaching methods

All of the classes spent approximately the same amount of time on the topic of electric circuits. The courses taken by students in groups A were traditional in format, having lectures, discussions and laboratories. The course taken by those in group B differed from the traditional format only in that they were based on a text that focused on qualitative reasoning, desk-top experiments, well-constructed explanations, and discussion with partners. They also developed an understanding of electric circuits and electrostatics from a perspective of models of microscopic processes.

The Israeli study[13] was done in the late 1980s while a new E&M course for high school students that explicitly deals with models of microscopic processes was under development. However, many Israeli teachers participated in in-service courses run by the Israeli development team.[20] In these courses the importance of dealing with models of microscopic processes was emphasized. For more details on the Israeli study, we refer the reader to Ref. 13.

B. Discussion of the questions

We chose the topic of transients in dc electric circuits because our hypothesis is that this is an area of E&M that requires a model of microscopic processes in order to develop a solid understanding. We suggest that to understand transients one needs to have some model of microscopic processes which will explain the mechanisms leading to the observed phenomena. We wanted to see if students had developed any model of microscopic phenomena to describe macroscopic observations, or whether they relied totally on equations. The two guidelines for our choice of questions were:

(i) that the students have the necessary background and knowledge base to answer the questions, and
(ii) that the questions be unfamiliar enough so that they could not be answered by simply reciting something they had heard or read.

The questionnaire can be found in the Appendix. Questions 1 and 2 relate to the circuit in Fig. 1. Questions 3 and 4 relate to the circuit in Fig. 2.

Questions 1–4 were also asked in the previous study of Israeli high school students.[13] Question 5 was not included in that study, and was designed to test whether students understood the process of "grounding" in an electric circuit.

Table I. Percentages of students answering questions 1 and 2 (see the Appendix) correctly, for groups A, B, and HS.

	Ammeter 1 Questions 1a, 2a		Ammeter 2 Questions 1b, 2b		Question 1c	Question 1d
	Correct answer	Correct explanation	Correct answer	Correct explanation	Correct answer	Correct answer
Group A	34%	18%	40%	18%	50%	68%
Group B	97%	90%	93%	90%	83%[a]	80%
HS	78%	78%	78%	78%	89%	81%

[a]The reader may wonder how a student could answer 2a and 2b (explanation) correctly while having incorrectly described what was happening (1c). Actually, three students in group B did just that. Apparently they had the wrong picture first, realized their mistake later, but did not go back to correct it.

III. RESULTS OF THE WRITTEN QUESTIONNAIRE

A. Circuit 1: Questions 1 and 2

Table I contains the percentages of students answering questions 1 and 2 correctly for each of the two groups in this study and also the results of the Israeli study[13] (HS, when reported). The lowest percentage of correct answers was from group A. It is interesting to note that for that group, even of those students who chose the correct answer, not more than half could back it by a correct explanation. This stands in sharp contrast to the situation with group B or HS students, who, when answering correctly, were also able to give a correct explanation. It is also interesting to compare the quality of the explanations of students in group A and group B. Here are two examples of how group A students who chose the correct answer to question 2a explained why the current initially jumps to some initial value and then gradually decreases to zero:

(1) *The current jumps because a potential difference has been introduced. The current decreases because as charge moves to the capacitor, the V decreases and equilibrium is reached, meaning no more charge will move.*

(2) *Charge moves until the capacitor is full, then the potential difference across the capacitor is the same as across the battery. Because there are no potential differences, it means no charge.*

Here are two examples of how group B students who chose the correct answer to question 2a explained the same issue:

(1) *The current jumps instantaneously to some initial value due to the electric fields in the circuit and the path being a closed path. The capacitor plates build up charge and the electric field outside the capacitor plates increases as charge on the plates increases. Eventually, the electric field is equal in magnitude and opposite in direction of the electric field due to the battery and the surface charges on the wires. As the electric field outside the capacitor plates increases, current decreases. When static equilibrium is reached due to the electric fields inside the circuit,* $E_{net}=0$ *and current stops flowing.*

(2) *At the moment the switch is closed, the capacitor has no effect on the circuit. The current shown by the ammeter would equal the current if no capacitor was in the circuit. After this small amount of time, the capacitor begins to charge. As the current decreases, the capacitor is becoming more charged. The electric field due to the capacitor is beginning to cancel the electric field due to the battery; therefore, less current. The current read by the ammeter will finally equal zero when the electric field from the capacitor cancels out the field from the battery. When there is no net field in the circuit, current equals zero.*

The difference in the argumentation between group A students and group B students is rather striking.

Table II lists the percentages of students from group A and group B choosing each category in questions 2a and 2b. Since most of the group B students answered this question correctly, we focus on the incorrect answers of group A students. About 30% of group A students who gave incorrect answers answered by trying to use equations they had memorized. Here is an example of an explanation given for why the current through ammeter **1** is zero:

Because the capacitance is so large and $V=Q/C$, *the voltage becomes very small, so small we say it equals zero. Also,* $V=IR$ *and since resistance is constant and* $V=0$, $I=0$.

Table II. Percentages of students choosing each category in their answers to questions 2a, 2b, for groups A and B.

Question 2a	Group A	Group B	Question 2b	Group A	Group B
(1)	8.9%	0%	(1)	3.3%	3.4%
(2)	13.3%	3.4%	(2)	34.4%	3.4%
(3)	33.3%	0%	(3)	18.9%	0%
(4)	34.4%	96.6%	(4)	38.9%	93.1%
(5)	10.0%	0%	(5)	4.4%	0%

The most common misunderstanding group A students had about circuit 1 (about 25%) was that the order of the elements mattered: the capacitor filled with charge flowing through one part of the circuit only. Researchers studying student understanding of circuits with only batteries and bulbs (see, for example, Refs. 14 and 15) have also noted this type of misconception. Some said that charge flowed from the positive terminal of the battery through ammeter **2** only, with no charge flowing through ammeter **1**. Others said that less flowed through ammeter **2** than through ammeter **1** because of the position of the resistor. About 10% of the students indicated that the capacitor would fill with charge on one side by current going through one ammeter and then, when "filled," charge would start to flow through the other ammeter. What seemed to be implicit in these answers was that students thought that charge somehow "jumped" from one plate of the capacitor to the other. In the interviews that followed, we actually found this picture to be quite common. A fairly large percentage (13%) of students in group A indicated that an ammeter read voltage, capacitance, or charge, and 7% clearly stated that they did not understand the relation between charge and current.

B. Circuit 2: Questions 3 and 4

The percentages of correct answers to questions 3 and 4 for each group of students are listed in Table III. The incorrect answers to question 3a from the students in group A were similar to their incorrect answers to questions 1 and 2. The most common categories of incorrect answers were:

(1) the use of memorized equations while misinterpreting their meaning (18%),
(2) the order of the elements in the circuit mattered (19%), and
(3) a statement that the ammeters read voltage (5%).

Assertions that the order of the elements mattered came in many forms. Some claimed that there would be a constant current in every ammeter, but that the magnitudes of these currents would be decreasing from one ammeter to the next (i.e., $i_1>i_3>i_2$). Others had all ammeters reading increasing currents up to a constant value, but with different ammeter readings increasing at different rates. The incorrect answers to question 3a from students in group B were mainly due to

Table III. Percentages of students answering questions 3 and 4 correctly, for groups A, B, and HS.

	Question 3a Correct	Question 3b Correct	Question 4a		Question 4b	
			Correct answer	Correct explanation	Correct answer	Correct explanation
Group A	14%	53%	73%	6%	84%	7%
Group B	62%	62%	90%	45%	97%	41%
HS	64%	67%	64%	64%	64%	64%

the notion that the order of the elements in the circuit mattered. In two cases the answers were simply incomplete.

As seen from Table III, very few of the students in group A, even when giving the correct answer in question 4, could back it up with a correct explanation. Half of the students in group B who answered correctly could explain their choices. This difference, in our opinion, clearly manifests the importance of emphasizing models of microscopic processes when dealing with this topic. The situation with the Israeli HS students (Grade 12) is very interesting: two-thirds of these students answered correctly, and were also able to explain their choices. As noted above, the teachers of these students participated in in-service courses run by the Israeli group,[20] in which the importance of models of microscopic processes was emphasized. Clearly this affected their teaching practices, and was reflected in the performance of their students.

In question 4b(2) students were asked about the source of the charges on the capacitor plates. The most common incorrect statement here was that the charges originated in the battery only (33% of group A students, 24% of group B students). Apparently the roles of the conductor and the battery need to be given more attention during instruction.

C. Grounding: Question 5

Table IV contains the percentage of students that answered the different parts of problem 5 correctly. Neither group of students had any instruction where grounding was specifically discussed. From the answers that group A students gave to problem 5a, we believe that many of them did not know what the words "net charge" meant. Most of the students who answered 5a correctly discussed the charge on one plate as being held in place due to the attractive force of the charge on the other plate. A few stated that in order to discharge the capacitor, both plates must be grounded, so as to form a complete circuit.

The majority of incorrect answers of group A students to part 5b indicated a misunderstanding of the meaning of potential difference (or voltage). Here are some examples of students' responses:

Table IV. Percentages of students answering the different parts of question 5 correctly, for Groups A and B.

	Question 5a		Question 5b	Question 5c	Question 5d
Correct answers	Charge on each plate	no net charge	Potential difference	Charge unchanged	pd unchanged
Group A	83%	39%	26%	13%	13%
Group B	100%	83%	52%	14%	17%

(1) *There would be a voltage "flowing" from plate A to plate B.*

(2) *The capacitor has to be in a complete circuit in order to have voltage.*

(3) *The voltage would be stored in the capacitor and discharged if the two plates were touched simultaneously.*

As for group B students, there were no errors which were common to many students.

The percentage of completely correct answer to questions 5c and 5d were about same (and small) for the two groups. In part 5c, 24% of group A students stated that charge would leave the grounded plate only. They did not give complete explanations of why they thought this would happen. An example of this type of response is:

> *Yes, because the ground will neutralize the plate that is connected to the ground.*

18% of these students said the charge would leave both plates. Many of them explicitly stated that the charge would jump from one plate to the other. Others implied it. Here are two examples.

(1) *Yes, the charge on the plate would go into the ground. Then some of the charge on the other plate would jump over.*

(2) *Charge on one would transfer to the other which would transfer charge to the ground.*

Another 14% of the group A students indicated that charge would leave the capacitor, but in explanation made vague statements like:

> *Yes, because the ground neutralizes the amount of charge.*

The rest of the answers were unclear or ambiguous. Students often tried to use words they had heard, but did not combine them into a meaningful explanation.

Among group B students, 66% said that charge would leave the plate that was grounded. Following are some examples of the type of answers they gave:

(1) *It Might. If plate A is connected then the negative charge ions should 'leak' off into the earth (or ground).*

(2) *Yes, because ground acts as a conductor which would draw charge off the plates.*
Yes, that plate would be neutralized since it is exposed to an infinite source of charges. The charge would flow off the plate, or charge would come from the ground until both are equal, making the charge on the plate zero.

Neither group A nor group B students discussed electric forces or electric fields in their explanations. Some did think of ground as a huge conductor that could give or absorb electrons, but without thinking about the electric forces, went on to incorrect conclusions. In total, the answers of the two groups of students were not very different on this question. This is an important (and somewhat discouraging) finding, since it indicates that even when instruction emphasizes microscopic mechanisms (as done for group B), students do not use these mechanisms when confronted with phenomena that are completely unfamiliar to them: transfer is of limited extent.

In part 5d, 11% of group A students gave the correct answer for wrong reasons or gave no explanation. 34% answered incorrectly, arguing that the charge on one plate changed, so the potential across the plates would change. The rest of the answers indicated (as in 5b) that they did not understand the concept of potential difference. 10% of group B students discussed the change in potential difference across the plates in terms of there being less charge on one plate. The rest discussed a change in the electric field, arguing that it would be "due to one plate only," if the charge left the other plate.

IV. INTERVIEWS

Most of the interviews with students from group A reflected a situation we have already alluded to in relation to the questionnaire: a lack of any clearly defined conceptions. Answers were often contrived, and words were frequently quoted without clear meaning.

In the following, we shall briefly sketch a typical interview. The student began by saying that ammeters indicated current and that the current in both ammeters in the circuit in Fig. 1 (see the Appendix) would rise to a constant value and stay there. He claimed that charges would collect on *both* plates of the capacitor, and that they would be of the *same sign*. When asked why charges would collect on the plates, his first response was: "*due to the voltage difference in the battery.*" This is an example of the type of initial response he would give to a question. He used terms he had heard, without necessarily thinking about their meaning. He then described the charge as coming out of the battery and jumping from one capacitor plate to the other. This idea of "jumping" was very common among students interviewed, although it was not so evident from the answers to the questionnaires. When asked why charges collect on the plates if they can jump across, he answered "*I just thought capacitors collected charge—something internal I can't understand.*" He persisted with the view of charge "jumping" across the plates even though the interviewer asked questions designed to probe deeper, to see if he would come up with a microscopic mechanism or change his theory. He later modified his description to say that the two plates had charges of opposite signs, but still insisted tenaciously: "*I just know it flows through the capacitor, that some stays on one plate and the other sign of charge jumps to the other plate.*" Later in the interview, he was asked whether charge would jump from one conducting plate to another, if the conductors were separated by air. After some discussion, he said, "*Is that what a capacitor is? Just two plates?*"

When discussing the first circuit (Fig. 1), this student did not use sequential reasoning ("the order of the elements in the circuit matters"). However, he did so when dealing with the second circuit (Fig. 2). He claimed that all the ammeters in this circuit would rise to a constant value when the switch was closed, but that ammeter 1 would have the largest current through it, ammeter 2 somewhat smaller, and ammeter 3 the smallest. He also said that there would be less charge on plates C and D than on plates A and B. Upon further questioning, he changed his statement to claim that there would be no charge on plates C and D and no current going through ammeters 2 and 3. It was clear that further questioning would not yield any further information about this student's conceptual framework. Eventually this student admitted that he was rather confused.

When asked how he would ground the capacitor in practice, he said he would touch it to the table or to himself: "*any neutral charged object connected to the earth would do.*" He said it did not matter whether it was a conductor or an insulator. This interview eventually moved into a mode where the interviewer set up the circuit, and let the student observe what was happening. At this stage, the scenario essentially changed from interviewing to teaching.

Most of the 20 interviews with group A students had a similar flavor, although they differed in the details of the arguments forwarded. Students would search for replies that would utilize phrases (and even equations) they had encountered, rather than try to base their response on a mental model of the physical situation. Some students even failed to see when they were contradicting themselves, but this was not always the case. Of the 20 students interviewed, 2 students demonstrated a very solid understanding of the concepts, an ability to think through an answer by analyzing a microscopic model, and the ability to build a new model when a failure in the one they were using became evident. However, one of these students had two years of high school physics and the other had two years of community college before taking this course.

The interviews with students from group B were quite different. When they did not initially know the correct answer, they would recognize inconsistencies in their models and were able to construct models based on microscopic processes easily. The idea of charge "jumping" from one capacitor plate to the other came up in two of these interviews, but it was quickly dispelled.

V. CONCLUSIONS

It is a well documented fact that many students have great difficulties in analyzing electric circuits in a qualitative manner.[3,6,7,9,10,13,14] Unlike the area of mechanics, where processes can be directly visualized, in electricity, everything which is actually seen is an indirect manifestation of some hidden microscopic process. We then hypothesized that understanding of macroscopic phenomena requires a coherent model of microscopic processes and that student difficulties in qualitative analysis of electric circuits could be overcome, if enough emphasis were placed on models of microscopic processes during instruction.

In the present study, we tried to see whether this assumption does indeed withstand an empirical test. A text recently developed[18] and used in instruction (group B) enabled us to do so. We compared students taught with an emphasis on microscopic models (group B) to students taught traditionally (group A). As far as we could determine, group A and group B students were of similar backgrounds and capabilities, and there was no *a priori* reason to expect one group to perform better than the other.

We found that group B students exhibited a superior understanding of the phenomena and were better able to give valid explanations in a variety of situations, including those which were less familiar to them, than group A students. The way they learned the subject enabled them to construct mental models, which they could apply to these situations. In contrast, group A students had great difficulties. Apparently, since their study of the subject was based mainly on equations and mathematical formulations, they did not construct robust models of the physical situation in their minds. Therefore, when confronted with new situations, they did not have any tools to analyze them. It was also very clear that the macroscopic parameters usually used in analyzing electric circuits (potential difference or voltage, current, resistance, capacitance, etc.) were not well internalized, and their meaning was rather vague.

Our conclusion from this study is that models of microscopic processes should be introduced as an integral part of any E&M course, in order to enable students to internalize the concepts involved, build coherent mental models, and be able to use them in analyzing and explaining physical phenomena.

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APPENDIX

The following questions concern the circuit shown in Fig. 1. The components of the circuit include a battery, switch S, capacitor with plates A and B, a resistor and two ammeters, 1 and 2. The resistance R is roughly 100Ω and the capacitance C is about 0.1 F. The exact values are not important. The capacitor is initially uncharged and the switch S is open.

1. Switch S is closed. Discuss qualitatively each of the following questions.

a) Describe qualitatively what ammeter 1 will read as a function of time, starting at the moment the switch is closed.

b) Describe qualitatively what ammeter 2 will read during the same time interval.

c) If at a certain moment ammeter 1 indicates a current i_1, and at that same moment ammeter 2 indicates current i_2, which of the following is correct?

(1) $i_2 < i_1$
(2) $i_2 = i_1$
(3) $i_2 > i_1$
(4) cannot determine

d) Initially, when switch S was open, plates A and B were not charged. From the moment S is closed (*circle all correct statements*):

(1) Will charges accumulate on plate A? If so, which (positive or negative)?
(2) Will charges accumulate on plate B? If so, which (positive or negative)?

2. The previous question asked about various phenomena. In this question, we ask about processes which explain these phenomena. We shall look at individual components of the circuit. After each question we suggest a number of possible answers. Choose one answer and explain your choice. In your explanations try to use some of the following terms: charge, current, force, electric field, potential, potential difference, voltage.

a) How does the current in ammeter 1 behave as a function of time from the moment the switch is closed?

(1) The current is zero and stays zero. Why?
(2) The current is constant, different from zero. Why?
(3) The current increases to a maximum value and stays constant at that value. Why does it increases initially, and why does it stay constant?
(4) The current jumps instantaneously to some initial value and then gradually decreases to zero. Why is there an initial current? Why does the current decrease? Why does it stop?
(5) Any other possibility. Describe and explain.

b) How does the current in ammeter 2 behave as a function of time from the moment the switch is closed?

(1) The current is zero and stays zero. Why?
(2) The current is constant, different from zero. Why?
(3) The current increases to a maximum value and stays constant at that value. Why does it increase initially, and why does it stay constant?
(4) The current jumps instantaneously to some initial value and then gradually decreases to zero. Why is there an initial current? Why does the current decrease? Why does it stop?
(5) Any other possibility. Describe and explain.

c) Recall that plates A and B are not charged initially, when switch S is open. After switch S is closed,

(1) no charges accumulate on the capacitor. Why?
(2) charges do accumulate on both plates. Why do charges accumulate? What is the source of these charges? (battery only, connecting wires only, both?) Assume that at a given moment charge Q_1 has accumulated on plate A and a charge Q_2 has accumulated on plate B. How is charge Q_1 related to charge Q_2? Refer to both magnitude and sign.
(3) Any other possibilities. Describe and explain.

3. A second circuit is shown in Fig. 2. In this circuit we have connected a battery, a switch S, three ammeters—1, 2, and 3, two capacitors, and two resistors. The resistances and capacitances are the same sizes as in the previous question. Initially, when the switch S is open, there is no charge on any of the capacitor plates.
Switch S is closed. Discuss each of the following questions qualitatively.

a) What will each of the three ammeters show from the moment the switch is closed and thereafter?

b) Plates A, B, C, and D were initially uncharged. From the moment switch S is closed, will charge accumulate on the plates? If so, which (positive or negative)?

4. The following questions refer to the part of the circuit composed of plate B, the connecting wire, ammeter 3, and plate D.
After each question we suggest a number of possible answers. Choose one answer and explain your choice.

a) From the moment the switch is closed, what does ammeter 3 indicate?

(1) The current is zero. Why?
(2) The current is not zero. Why? How does the current change with time?

b) Remember that plates B and D were not charged when switch S was open. After it is closed,

(1) no charges accumulate on plates B and D. Why?
(2) there will be charges on plates B and D. Why do the charges accumulate? What is the source of these charges? Assume charge Q_B is on plate B, and charge Q_D is on plate D. What is the relationship between Q_B and Q_D? Refer to both magnitude and sign.

5. Consider what would happen if, after the switch S had been closed for a long time, the capacitor was removed from the circuit (without touching the capacitor leads).

a) Would there be charge on either plate of the capacitor? What would be the net charge on the capacitor? Explain.

b) Would there be a potential difference across the capacitor? Explain.

c) If one plate of the capacitor were then connected to ground, would the charge on either plate change? Explain your answer.

d) If one plate of the capacitor were connected to ground, would the potential difference change? Explain your answer.

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> Science is a way to teach how something gets to be known, what is not known, to what extent things *are* known (for nothing is known absolutely), how to handle doubt and uncertainty, what the rules of evidence are, how to think about things so that judgments can be made, how to distinguish truth from fraud, and from show.
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