How to teach about transition processes and other more complex factors in so-called simple electric circuits

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Abstract

Much effort has been invested over many years in the study of so-called misconceptions about the electric circuit, which students hold when arriving at the classroom. Not much success, however, can be reported in fostering a long lasting conceptual change in students towards a scientifically acceptable perspective. One reason for this failure is seen in the fact that the content is presented partly as too simple, partly as too abstract and finally without a causal interrelation. This statement will be discussed along the topics "the electric circuit as a system", potential difference and surface charges" and "transition processes and stationary states.

Keywords: Electric circuit, system thinking, potential difference, surface charges, simulation program, transition process

Introduction

If a group of newcomers were introduced to mountain climbing with the aim of mastering the more demanding parts of this activity, the degree of difficulty would have to be to be matched to the newcomers' ability. The goal should be that every member of the group would be able to reach the top of the mountain and so enjoy the completion of a difficult and important task. If the task is too simple or too difficult, the climbers may give up and re-orient to other kinds of sport.

Applied to the objectives of physics, learning research over the last 30 years tells us that the majority of our students do not reach the goal of understanding some basic features of the so-called simple electric circuit (see the symposium "Research as a guide to improving university-level instruction on electricity and magnetism" in this volume).

Much effort has been invested over many years in the study of so-called misconceptions, which students hold when arriving at the classroom. Not much success, however, can be reported in fostering a long lasting conceptual change in students towards a scientifically acceptable perspective.

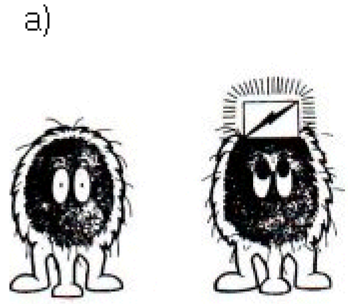
A critical analysis of the traditional curriculum and its relation to the chosen degree of difficulty may be helpful in the search for a reason for this failure.

In our opinion the way the content to be learned is presented in most textbooks is partly too simple, partly too abstract and finally without a causal interrelation.

This statement will be exemplified not only - as indicated in the title - in respect to transition processes but also by addressing two problematic points: "system aspect of the electric circuit" and "definition of potential difference".

The electric circuit as a system

Well known misconceptions about the electric circuit are characterized by the common supposition that energy enriched matter is moving around in a circular system. This idea is not confined to students; it also appears in textbooks. A typical example from an American textbook is shown in Fig. 1.



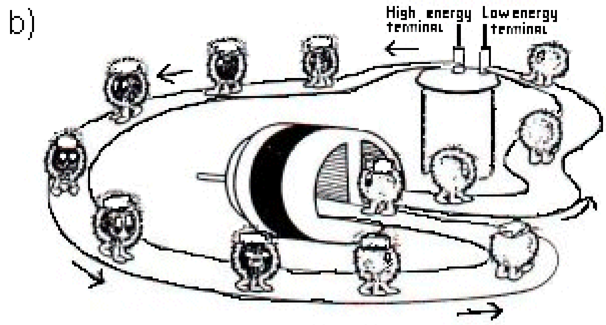


Fig. 1: a) Electric particles with and without Energy

b) Electric particles carry energy from the battery to the motor and return back without energy

Electric particles, which can evidently move by themselves, are charged with energy at the battery. They carry their energy package to the motor and return "exhausted" back to the battery. In a relatively modern German textbook the electric current is compared with a bunch of skiers on a trail or loaded trucks on a highway. Other authors have proposed comparisons with a hot water heating system or a conveyor belt.
A little thought will reveal that these models lead to serious contradictions because they are all missing an essential feature of the electric circuit: a force bound interrelation between source and load. It is not energy enriched matter which is transported. Instead, work is performed by pulling and pushing charge carriers around or back and forth. The German expression "Kraftwerk" (force plant) for a power plant specifies correctly this point.
A bicycle chain or a circular water system under high pressure and with a low drift velocity are more acceptable models. No energy enriched matter is transported, but force and motion are. To reach a deeper understanding (and hopefully) an ongoing interest in physics, it seems necessary to discuss this fact explicitly and repetitively with students when explaining the outcome of experiments; this in contrast with the misconceptions mentioned above.
This approach to system thinking is a quite difficult learning task. It is not sufficient to learn simple rules like: the larger the resistor the smaller the current, instead one must consider possible feedback loops and time delays. Both effort and repetitive exercise are necessary to master this part of "mountain climbing". Intermediate levels of difficulty should be introduced and any indication of progress is a worthwhile step along the road to more complex and abstract thinking. For further information about this topic and possible classroom activities see Haertel (1975).

Potential difference and surface charges

It is common practice to introduce the electric current qualitatively as drifting free electrons. Any such qualitative interpretation, however, is missing when the equally important basic term "potential difference" is introduced. The expression "energy per charge" defines how to measure potential difference. It is not suitable to derive any causal explanation for processes within electric circuits.
What is on a microscopic level the difference between cross sections A and B at the input

and output of a current carrying resistor (Fig. 2)?

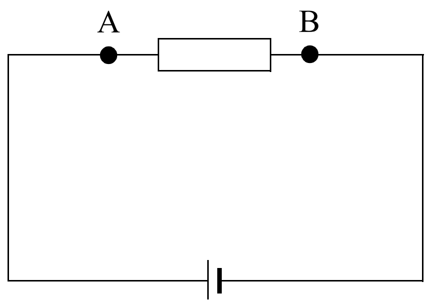


Fig. 2: What is the difference on a microscopic level between the cross sections at A and B?

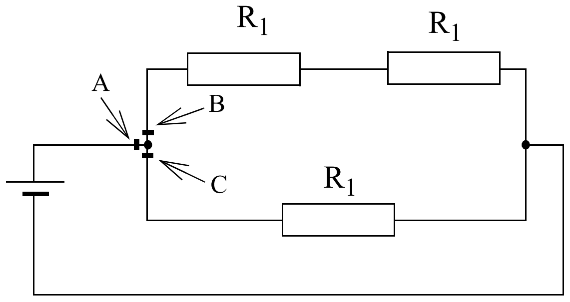


Fig. 3: What kind of difference at the cross section A, B and C is causing the distribution of current flow corresponding to the distant resistors?

Is there a difference between the cross section close to a branching point, which causes the distribution of the drifting electrons in respect to the resistors far ahead (Fig. 3)?
What is the origin of the strong electric field inside a resistor in comparison with the much weaker field inside the connecting conductors?
Why is the electric field within a current carrying resistive wire always oriented parallel to the axis of the wire, independent of any curvature?
These rather simple but basic questions cannot be answered if students know only the definition for potential difference given above.
Data from tests and interviews with students show that the term "potential difference" is seen as one of the most difficult to understand and that the majority of our students fail to do so. What are the consequences of such a failure to understand basic terms in physics? How many students may give up any interest in physics (no "climbing in the rocks" any more), judging their own intellectual competence to be insufficient for such demanding tasks?
At least in respect to the term "potential difference" this is somewhat academic, since a qualitative introduction to this term is possible, which could help to minimize the risk of failure. The key is surface charge: any conductor which is carrying a current will show additional charges on its surface. By the middle of the 19th century the German physicist Wilhelm Weber had shown that a circuit, when carrying a current, is neutral in total but shows different densities of surface charges on its different parts. Any two points of a circuit showing a potential difference will therefore show a difference in surface charges. This definition does not include any effects due to non-coulomb electromotive forces which will have to be added later.
A detailed description of the historical development of this approach, descriptions of experiments to demonstrate the existence of surface charges and detailed mathematical derivations have been published by Assis (2007).
A curriculum with a detailed treatment of surface charges has been published by Chabay

and Sherwood (2002) where representations like Fig. 4. are used.

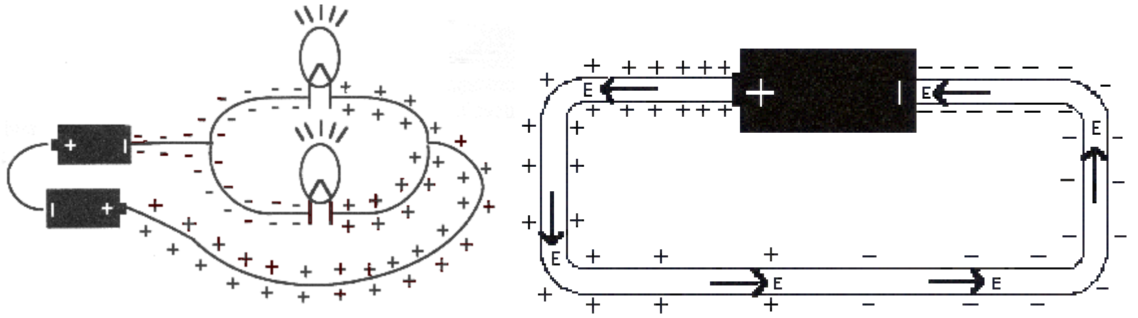


Fig. 4: left: Surface charges on parallel circuit
right: Approximate surface charge distribution in steady state (Chabay/Sherwood)

Some support when discussing the relation between potential and surface charges is offered by the simulation program CLOC, described below.

Transition processes and stationary states

Ohm´s law and Kirchhoff´s rules are part of the physics curriculum in practically all schools where physics is taught. But it is equally common to discuss only the steady states, which are controlled by these laws without explaining, or even mentioning, the transition processes which are necessary to reach any of these states.

These transition processes are rather rapid, so are difficult to measure and not so easy to explain. This may be a technical excuse for putting them to one side. But if precise observation and exact thinking are among the ultimate goals of physics education, such an approach is questionable. Students learn that when dealing with electric circuits there are only steady states. The question of how a battery „gets to know“ that somewhere far away a resistor has changed is not answered. The same holds for the question, how fast will a current rise to „infinity“ if a battery is shorted by a long conductor. Do our students learn that very fast processes are not important? Do they learn that action at a distance is an acceptable way to answer such questions? If students do not pose such questions, should they not be encouraged to recognize that transition processes are as important and necessary as steady states to establish a complete causal description and explanation of the electric circuit?

Such transition processes can be demonstrated experimentally by connecting a large capacitor in parallel to a load - a lamp - in a circuit (Fig.5).

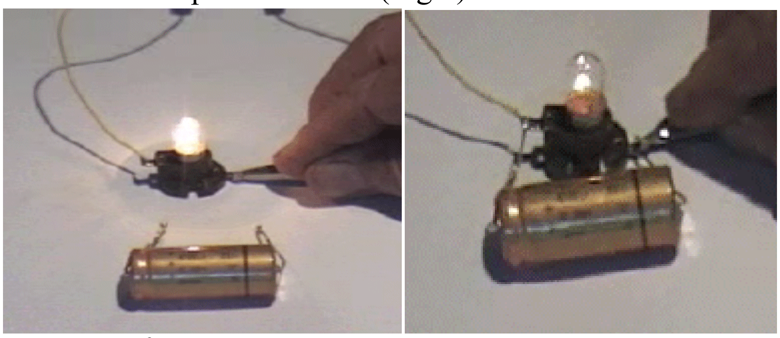


Fig. 5: Demonstration of a transition process

This corresponds qualitatively to reality since the conductors, connecting the battery with the load, form with their surfaces a capacitor which has to be loaded by surface charges, or its charges be re-arranged, during any transition process.

A simulation program named CLOC (Conceptual Learning Of Circuits) has been developed mainly, as the title indicates, to support general teaching and learning about circuits. It may, however, also be useful to demonstrate and explain the distribution of surface charges.

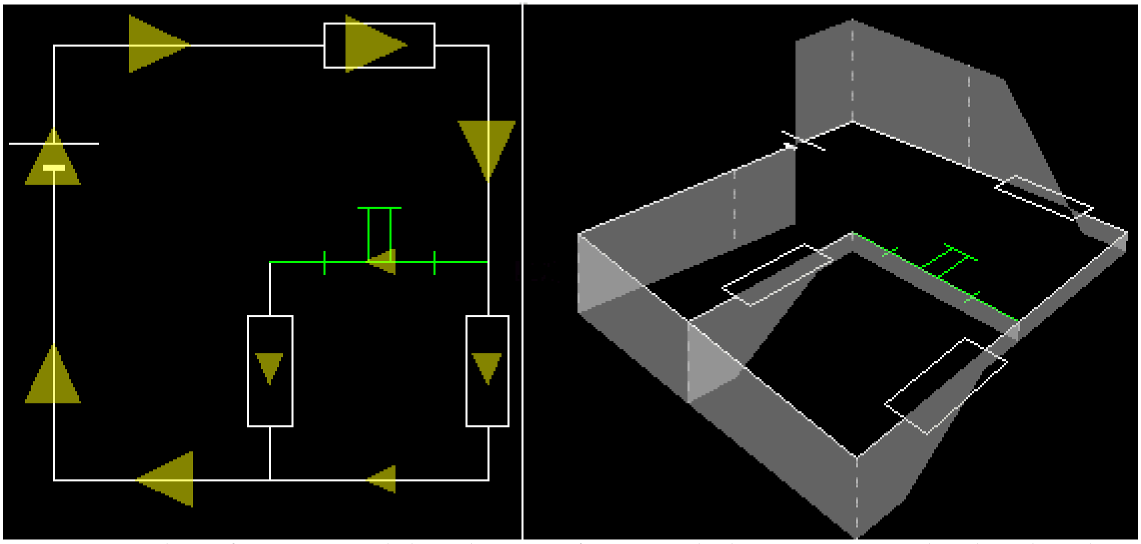


Fig. 6: Display of current and distribution of potential along circuits, edited within the simulation program CLOC (Conceptual Learning of Circuits)

CLOC describes the transport of matter between two abutting containers with a linear relation between the difference of container content and current flow. The algorithm controls step by step the equalization of these containers, revealing a transition process which is dependant on the size and number of the connected resistors.

When applied to a circular system like the electric circuit, this model provides the correct final stationary states, for which Ohm´s law and Kirchhoff´s rules are valid. The transition processes leading to these stationary states are, however, rather exaggerated and correspond to circuits where large capacitors are added in parallel to all resistors. With transition processes as the learning goal, however, such an exaggeration seems to be acceptable.

When running as an applet, CLOC can be controlled by JavaScript commands. If wanted, the display of the delay before the final steady state is reached can be hidden by using a suitable JavaScript command.

When used as an editor, CLOC allows the construction of any kind of circuit with the elements conductor, battery (only one per circuit) resistor and (interactive) switch. The strength of the current is displayed numerically and graphically. In a separate window the distribution of potential along the circuit is shown in 3d, allowing different viewing perspectives (Fig.6).

Once the existence of transition processes in electric circuits has been demonstrated in such an exaggerated form as presented by the program, teachers may wish to complement this approach with the phenomena in a normal circuit without additional capacitors. This is possible using the simulation program "TL-Transmission Line" whose algorithm is based on the solution of Maxwell´s equations in one dimension.

This program displays in two separate diagrams the distribution of potential difference and current along a double line with and without losses on the line. In addition resistors can be placed at selected locations to visualize the transmission and reflection processes for a simple serial and parallel circuit (Fig. 7).

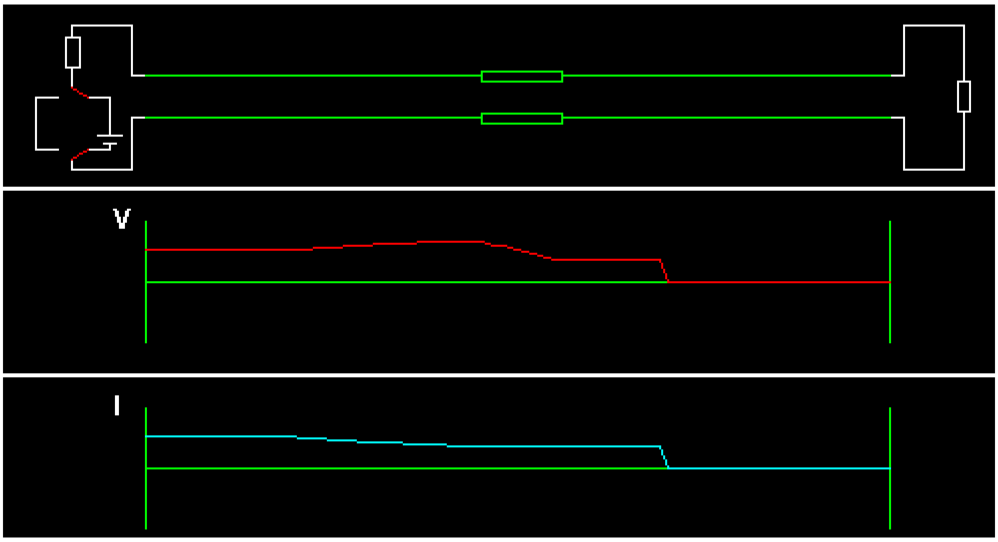


Fig. 7: Display of potential and current along a double line (with additional resistors) based on the solution of Maxwell´s equations in 1 dimension.

All parameters specifying the source, the load and line properties are interactively accessible, so that any kind of transition process can be visualized in real time. The algorithm has proven to be stable under all possible border conditions and has never showed artificial effects due to inappropriate numerical methods.

Final remark

The task for teachers is to present the complex properties of the electric circuit in a didactic form appropriate to the age and knowledge level of the learners. This, however, can only be done successfully when starting from a state of knowledge in correspondence with the facts. At very least one should not be tempted by the description in traditional textbooks of a "simple electric circuit" to believe that the learning task for students will be equally straightforward.

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For further publications and access to the presented programs see :
http://www.astrophysik.uni-kiel.de/~hhaertel