Voltage and Surface Charges

What Wilhelm Weber already knew 150 years ago

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Abstract

The abstract definition of electric power as "the ability of a voltage source to do work“ or quantitatively as "energy per unit charge" is preceded by a qualitative description in terms of the existence of surface charges. These surface charges and the associated electric fields can be demonstrated experimentally and allow a causal explanation of the processes and laws to be understood and learned.

1. Potential difference - one of the more difficult terms

Electric current is usually described qualitatively as being due to drifting electrons. However, a corresponding qualitative description for the terms "voltage" or "potential difference" is rarely found in textbooks. Voltage is described as the capacity of an electrical energy source to do work and quantitatively defined as energy per charge.
From a physical perspective there is nothing wrong with this mathematically elegant description, but it fails to provide a causal explanation for the processes inside electrical circuits.
As an illustration of the difficulty we can ask some simple questions.
In figure 1, what kind of difference in physical state (on a microscopic level) between points A and B of a voltage source is responsible for the existence of a potential difference?

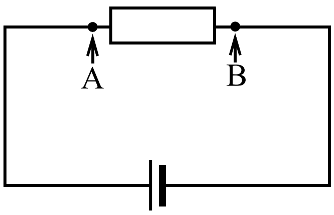

Fig. 1. What difference exists between the conductors at A and B?

Figure 2 shows that a much stronger field inside a resistor exists compared to the very weak field in the connecting conductors. How can this difference be explained through the definition of "energy per charge" ?.

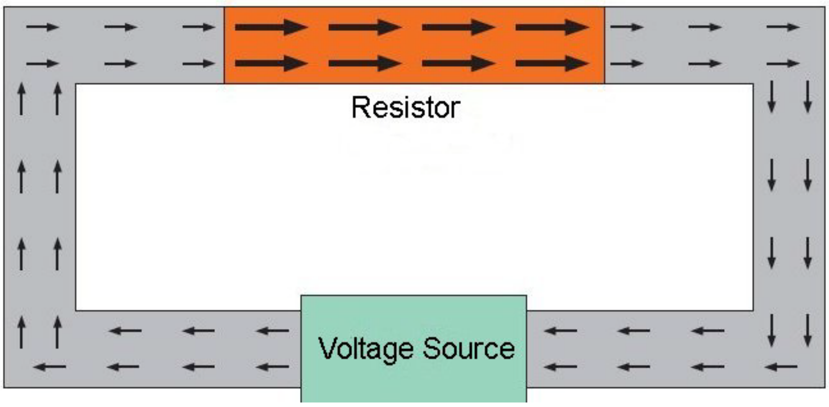

Fig. 2. Which charges cause the strong field inside the resistor?

A final example: The electric field inside a conductor connected to a battery is constant and axially oriented, independent of the conductor's length and curvature. Why is this? What makes the electric field follow the curvature of the wire? Where are the charges responsible for creating this electric field? Are all of them located at the battery?" According to Coulomb´s law (the most basic relation between charge and field) the separated charges at the outlet of the battery can only cause a distance-dependent field.

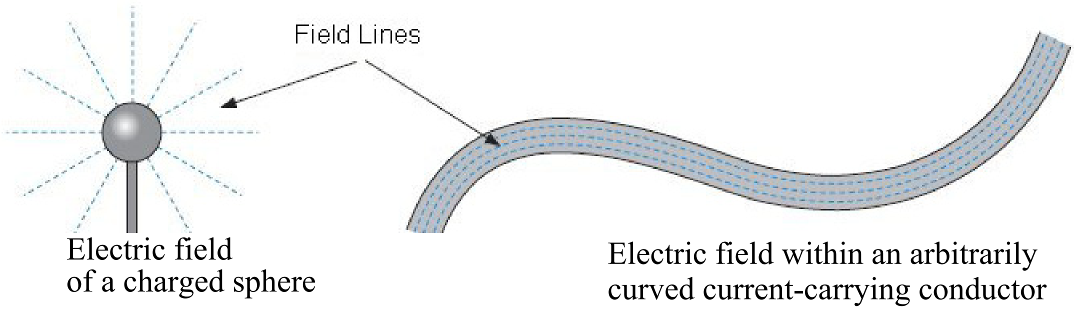

Fig. 3. Why is the field inside the conductor constant and independent of distance?

Test results show [1] that these and similar questions cannot be answered by the vast majority of our pupils or even by many physics teachers.
Interviews reveal that students find the concept of voltage difficult or incomprehensible. It is not known how many students lose interest in physics because they fail to understand basic concepts, but this number may be quite high. It is therefore astonishing that this unsatisfactory situation is accepted by most physics teachers and authors of textbooks, since an alternative explanation has been known for well over one hundred years.

2. Voltage and surface charges

The solution was described over 150 years ago. In 1852, Wilhelm Weber pointed out that although a current-carrying conductor is neutral overall, on its surface it carries charges of different density [2].
Recognizing that a potential difference between two points within an electric circuit is related to a difference in surface charges one can answer the questions above.
Figure 1: The conductor at points A and B carries positive and negative surface charges respectively.
Figure 2: The cross sections outside and inside the resistor are regions where the conductivity varies by many orders of magnitude. Electrons and positive charges respectively will accumulate in these regions and it is the field arising from these charges which will drive the current through the resistor (Figure 4).

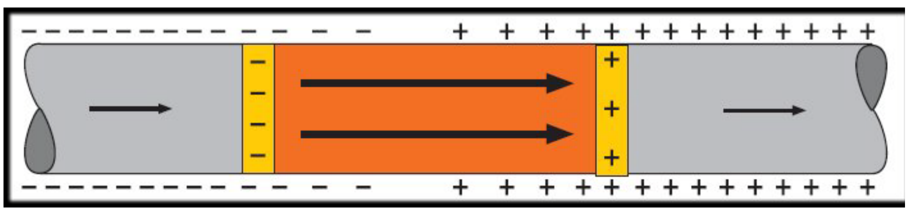

Fig. 4. Charged separating layers between resistor and conductor.

The validity of this statement can be derived directly from the Gaussian law. According to

Gauss, the flux through a closed surface is proportional to the enclosed charges.

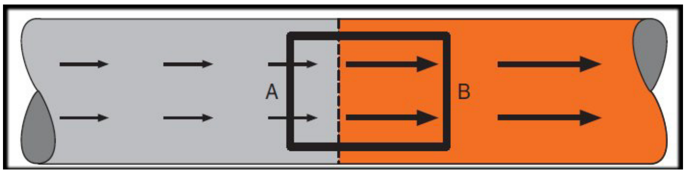

Fig. 5. Application of Gauss law at the interface between a conductor and a resistor.

Placing a cylindrical surface within a conductor and resistor such that the boundary surface is enclosed (shown as a dashed line in Figure 5), results in a different flow through the two end faces A and B. Therefore, a corresponding electric charge must exist at this interface between regions of high and low conductivity.
Figure 3: Surface charges on a straight, infinitely long conductor will produce an axially oriented constant electric field, if the gradient of the surface density is linear (Figure 6) to generate a constant electric field inside a rectilinear conductor.

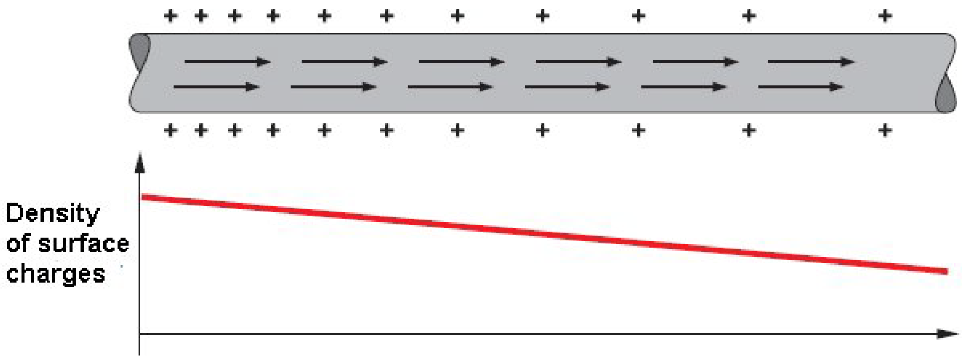

Fig. 6. Linear gradient of the surface charge density.

The gradient of surface charge density will depart from linearity if the conductor is curved. More electrons will accumulate on the "outside" of a curved conductor than on the inside, thereby creating a curved and precisely axially oriented path of the drifting conduction electrons. A similar argument applies for positively charged conductor sections.

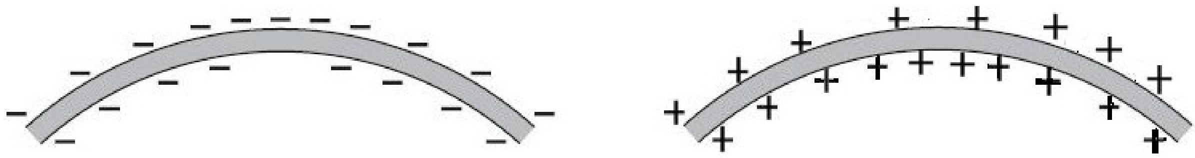

Fig. 7. Distribution of surface charges on curved conductors (qualitative).

The literature contains numerous references to the relationship between voltage and surface charges [3-8], but this relationship has generated little attention within the scientific community. It is reasonable to assume that this failure to link surface charge and voltage will have made it harder for many students to understand basic concepts, and thus may have led to a loss of interest in the subject. A proper investigation into this hypothesis would be valuable.
A description of the historical development of knowledge of surface charges in any current-carrying conductor, details of experiments for their detection and a detailed theoretical derivation has been given by Assis and Hernandes [9].

3. Instructions for teaching

If the concept of voltage or potential difference is related first to surface charges and the quantitative description in terms of energy per charge introduced only later, then certain facts must be taught at the start. In addition, particular learning steps are required, accompanied of course by appropriate demonstrations and classroom activities.

3.1. Charge, Coulomb force, charging of metal (Faraday cage)

An initial knowledge of the phenomenon of charge is required, together with some basic facts about the nature of the interaction between charge carriers of different polarity (Coulomb's law). It must also be known that free charges cannot exist inside a metallic conductor. A charged conductor carries free, non-neutralized charge carriers only on its surface.

It is not easy to explain why the surface of a metal acts as a barrier for electrons; this must for the present be accepted as fact. However, it should be noted that this surface barrier is not insurmountable. Before electronic tubes were replaced by transistors, free electrons outside metallic conductors were produced by heating a current-carrying conductor.

3.2. Functioning of a power source

At its simplest, an electric power source consists of a conductive device connected to the outside by two metallic contacts. The source has a further essential property: it can apply a force on the internal electrons to move them from one external contact towards the other. The kind of force varies with the type of power source. Within a battery chemical forces are active; within a generator electromagnetic forces can be applied.

Although the types of force differ, their action is always the same: at one external contact an excess of electrons will build up. These electrons are missing at the other contact, giving rise to a positive charge.

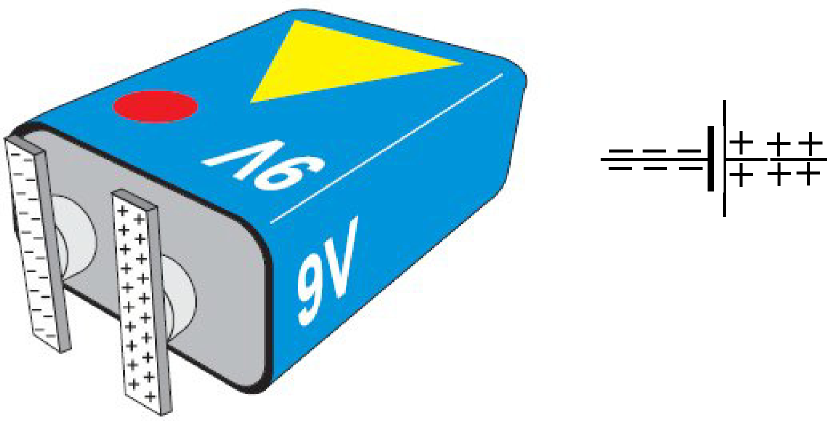

Fig. 8. A battery as voltage source with surface charges on its metallic outlets

The greater the density of the additional negative charges at the surface of the metallic contacts, the greater the repulsion between them.

The same holds for the positive charge carriers at the opposite side which attract the displacing electrons. A certain limit will be reached, which is characteristic for the specific power source, where these repelling and attracting Coulomb forces respectively will prevent any further accumulation of electrons. A state of equilibrium will then be established between the internal force of the power source and the back-driving Coulomb forces.

3.3. Surface charges on conductors

Connecting the contacts of a power source with metallic conductors is in principle not different from increasing the surface of these contacts.

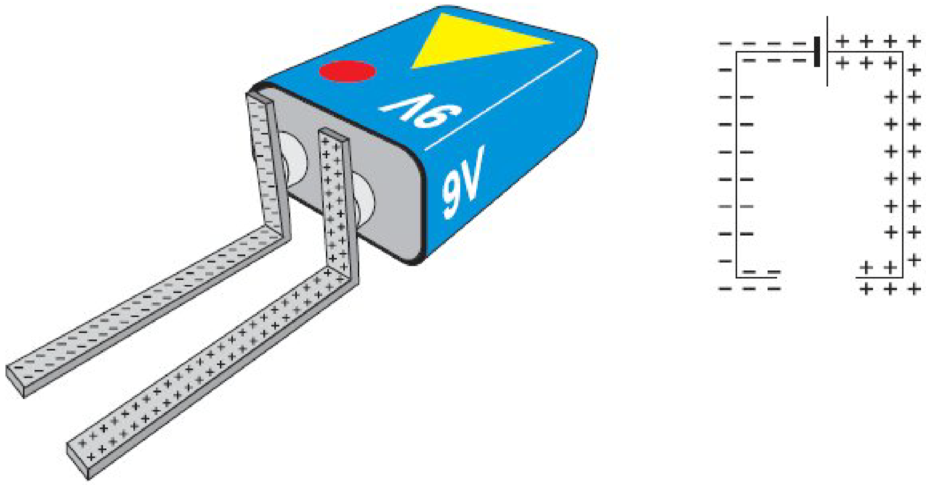

Fig. 9. Power source with connected conductors and surface charges

In an effort to minimize their mutual repulsion, these charge carriers will redistribute on this enlarged surface and in this way reduce their density. This implies a short period of non-equilibrium between the internal force of the power source and the Coulomb forces, during which additional electrons will be pushed on to these enlarged surfaces until the original density and an equilibrium between the involved forces is re-established.

3.4. Surface charges within a closed circuit

If the conductors are connected by a resistor and if the power source is strong enough to replace the electrons drifting through the resistor, a circular current will result, in which all electrons inside the conductors will take part.

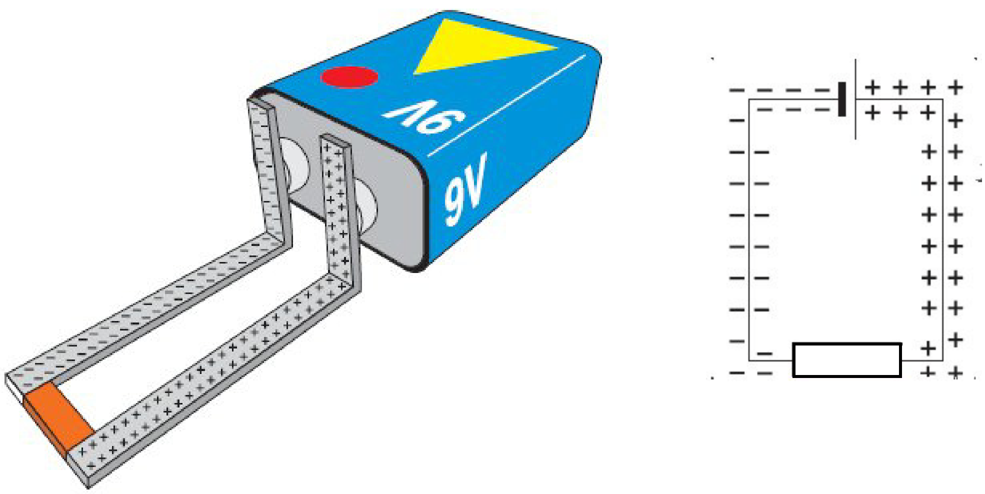

Fig. 10. A closed circuit and surface charges.

As long as the driving force of the power source remains constant the charges on the surfaces of the conductors will remain; however the electrons will start drifting along the closed circuit, together with the bulk of internal charges.

3.5. Potential difference and pressure difference in water circuits

A mechanical system like a water circuit can be regarded as a model for the electric circuit, treating the phenomena of current and pressure as analogous to electric current and voltage. To use a water circuit as a model, the kinetic energy of the flowing water must be negligible, which

requires that the drift velocity of the water must be small. To achieve significant energy transfer, large pressure differences must be assumed. The distribution of pressure can be demonstrated along series and parallel circuits with the help of pressure gauges or water columns; an analogy can then be made with electric circuits.
This method was applied during the development of the IPN teaching unit on the electric circuit and supported by the following figures and experiments:

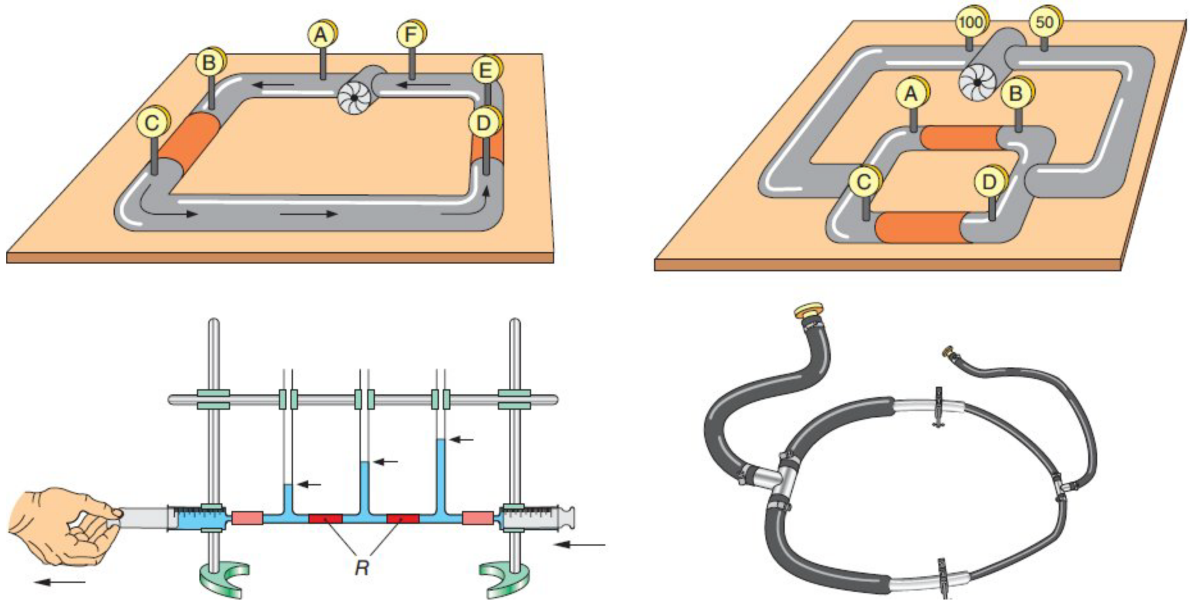

Fig. 11. Figures and setups to demonstrate pressure differences along water circuits.

Experience during the development of the IPN-teaching unit has shown that the water model supports communication between teachers and students while the latter try to develop their understanding of the electric circuit, a concept which is not directly accessible to our senses.
However, as shown in detail in an earlier article and confirmed by previous studies [11], we should not expect to much from the analogy between pressure difference and potential difference in respect to learning and understanding. The difference in pressure in a liquid is caused by its compressibility, the liquid at different locations is differently compressed. Students generally do not know this, and cannot fully appreciate the topic just by talking about compressibility. A careful and sophisticated analysis is needed to determine the pressure gradient along serial and parallel circuits and to explain the conditions for a steady state.
If such an analysis can be performed, it may be helpful consider a flow of water as movement of a compression wave front. When such a wave front impacts on a resistor, a backflow is created by short term congestion in front of the resistor. This backflow reduces the inflow rate until a steady state is reached between in- and outflow. To maintain a constant flow through any resistor, the inlet pressure must exceed the outlet pressure. This means that the compression of the flowing water at the outlet is reduced, in other words the water expends itself while passing through the resistor.
The same situation develops at every resistor which the wave front has to pass on its path around the circuit. In the equilibrium state a pressure difference will exist across each resistor in proportion to its resistance.
The same analysis can be applied to explain the origin and distribution of surface charges on a current carrying conductor. Conduction electrons can be regarded as a kind of "electron gas" which can be compressed or stretched a little bit by a voltage source. However, this causes only a compaction or dilution of the "electron gas" on the surfaces of the conductors and not, as in the case of a mechanical flow of water, over the entire cross-section. Water molecules can react

on the basis of short-range forces only with immediately adjacent neighbours and water can therefore be condensed over the complete cross section. Electrons interact via long-range Coulomb forces, they repel each other at long distances and can only be neutralized inside a metallic conductor by exactly the same amount of positive charge carriers. But on the surface of a conductor and only on the surface, additional charge carriers can exist.

3.6. Opportunities for experiments

3.6.1. Demonstration of surface charges

By 1962 Jefimenko had demonstrated quite simply the existence of surface charges on current carrying resistors [12]. Strips of red ink painted on glass plates served as resistors to which a relatively high voltage (> 10kV) was applied. The visualization of an electric field inside and outside the resistor was performed by scattered grass seeds which align with the electric field. Grass seeds are characterized by extremely fine tips at each end, which, in the presence of an electric field, favour the formation of a relatively large dipole moment. In addition, grass seeds have a small area of support, which reduces friction when they move; light tapping on the supporting glass plate encourages the seeds to align with the field.

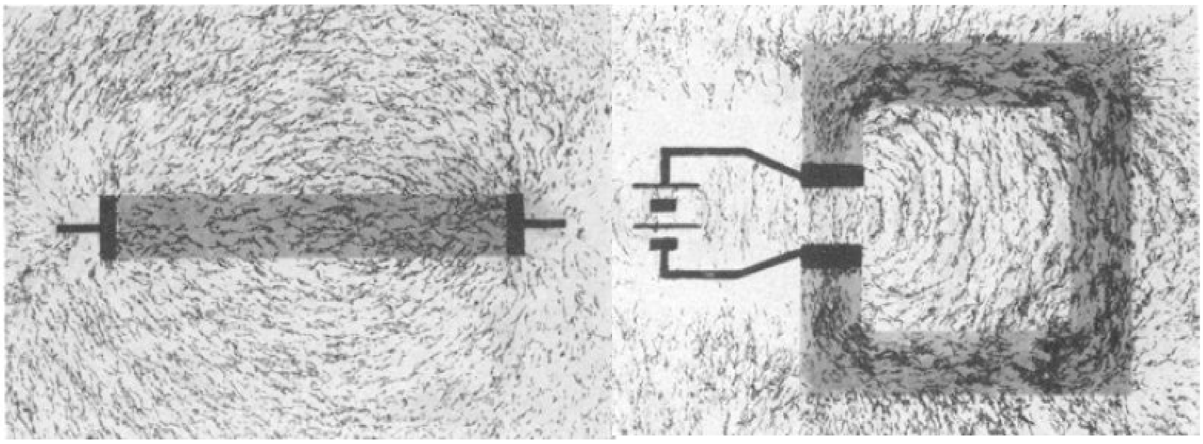

Fig. 12. Electric fields inside and outside differently formed resistors,
as visualized by scattered grass seeds [12].

3.6.2. Interaction of surface charges with external charges

Direct detection of the interaction of surface charges with an external charged object can be achieved if relatively large resistances and large potential differences are used.

Under those experimental conditions a movable charged metallic foil shows a clearly visible deflection along a chain of current carrying resistors (Figure 13). In this experiment, a voltage of 10 kV is applied to a series circuit, consisting of 4 resistors, and the deflection of a charged metal foil is studied when placed at different locations along the circuit [13].

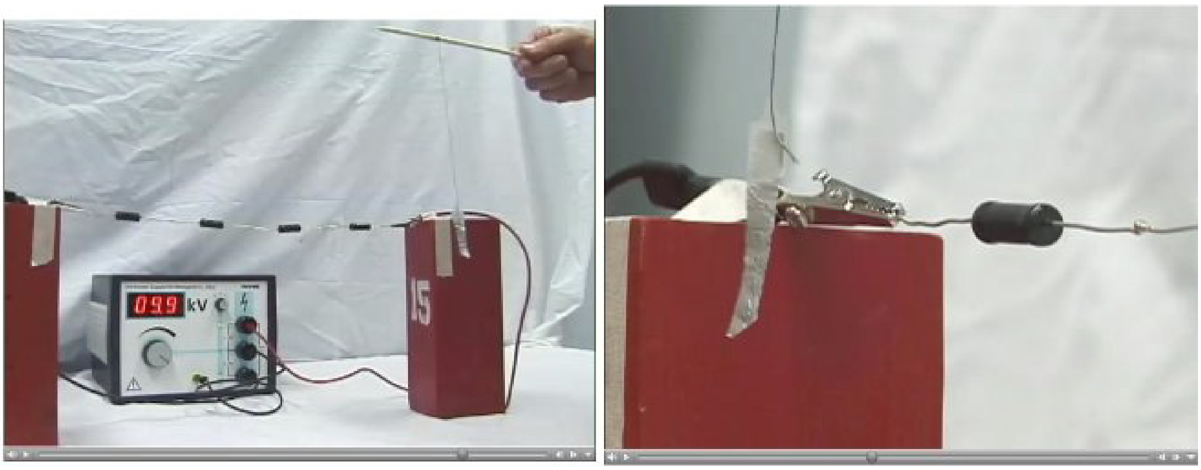

Fig. 13. Interaction between a current carrying conductor and a
charged metallic foil to demonstrate the existence of surface charges.

The experiment clearly demonstrates a lack of interaction close to the centre of the circuit. When brought in contact with both ends of the circuit, however, the foil is repelled due to electrostatic induction.

By replacing the metallic foil with a charged insulator (a straw, suspended at its centre, with graphite coated ends) the different polarity of the surface charges at the ends of the resistor chain can be demonstrated [14].

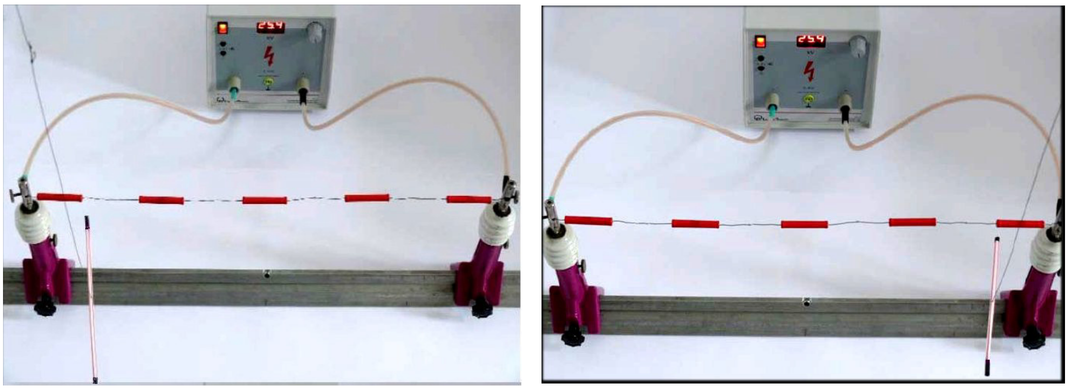

Fig. 14. Interaction between a current carrying chain of resistors and
a charged straw to demonstrate the existence of surface charges.

3.7. A successful course as challenge

In the U.S., a course on "Electric and Magnetic Interaction" has appeared, making extensive use of the following pictures [15].

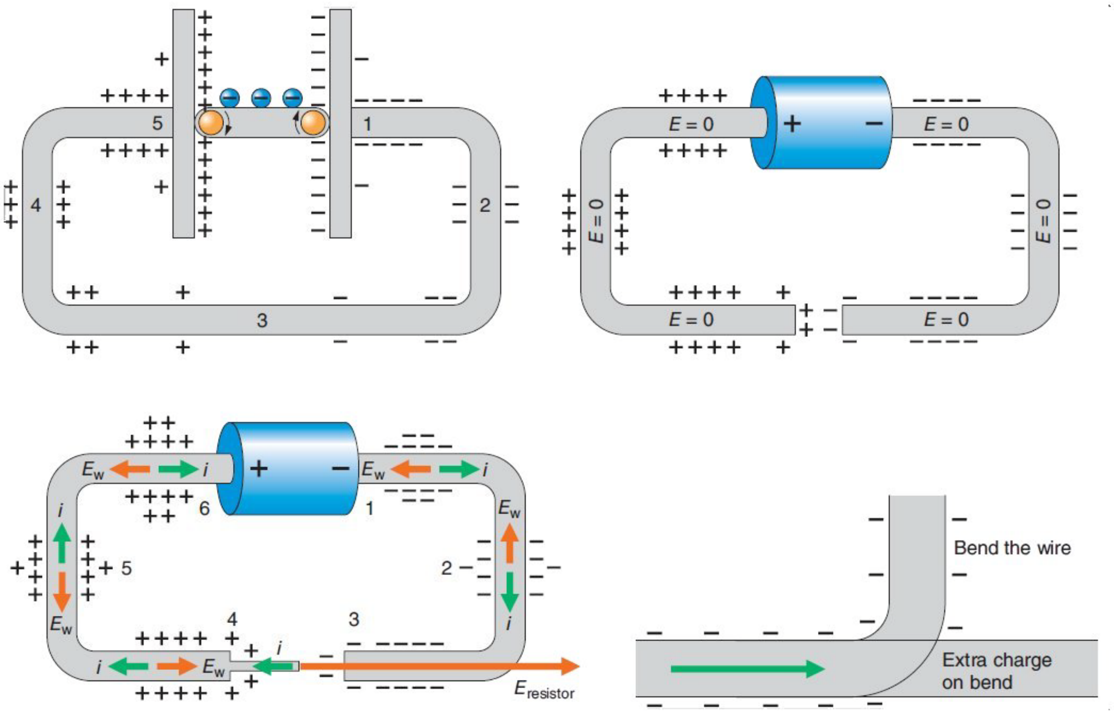

Fig. 15. Pictures from an American course to represent the distribution of surface charges[15].

These pictures are used to explain the origin of the driving force on electrons in an arbitrarily shaped conductor, why reducing the cross section of a wire implies an increased resistance, which charges are related to the strong field inside a resistor etc.

Such pictures can - even when incomplete - stimulate class discussion or can be used as an exercise to develop a more accurate and detailed insight into the electric circuit as a system which is simultaneously both simple and complex.

4. Conclusion

The introduction of potential difference or voltage as the working ability of a battery and in quantitative form as energy per charge is one-sided in its mathematical orientation. From a teaching perspective, this approach can be criticized as both too abstract and unintuitive. It hides the relation between voltage and surface charges and thus takes from students the chance to develop their physical intuition.

If students do not ask without prompting what voltage actually is, they should be encouraged to raise such questions and to find answers by studying the examples given above. However students react, the arguments given here should find a place in a qualified lesson plan, so that teachers can at any time deal appropriately with students' questions, or can stimulate discussion by raising such questions.

Literature

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