Voltage and Surface Charges

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ABSTRACT

The abstract definition of electric power as "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.

Keywords: Electric circuit, surface charge, electric field, voltage, Gauss Law, Coulomb force, pressure in liquids.

POTENTIAL DIFFERENCE

As a rule, the electrical current is qualitatively characterized as drifting electrons. In contrast, the introduction of the term "voltage" or "potential difference" in textbooks usually lacks a qualitative interpretation. Voltage is described as the ability of an electrical energy source to do work and is quantitatively defined as energy per charge - $U = E/q$. From a point of view in physics, there is nothing wrong with this mathematically elegant method. It is, however, not suitable for deriving a causal reason for processes in the electrical circuit.

To illustrate this difficulty, we can ask some simple questions.

- What kind of difference on a microscopic level is responsible for the existence of a potential difference between points A and B as indicate in figure 1?

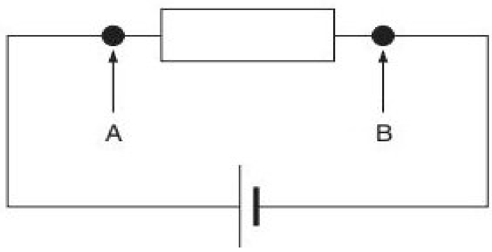

Figure 1. *Is There a Difference on a Microphysical Level between the Conductor Cross Sections at A and B?*

As indicated in figure 2, there exists a much stronger field inside a resistor compared to the very weak field in the wires connecting the resistor to the voltage source. This question cannot be answered due to the definition of "energy per charge".

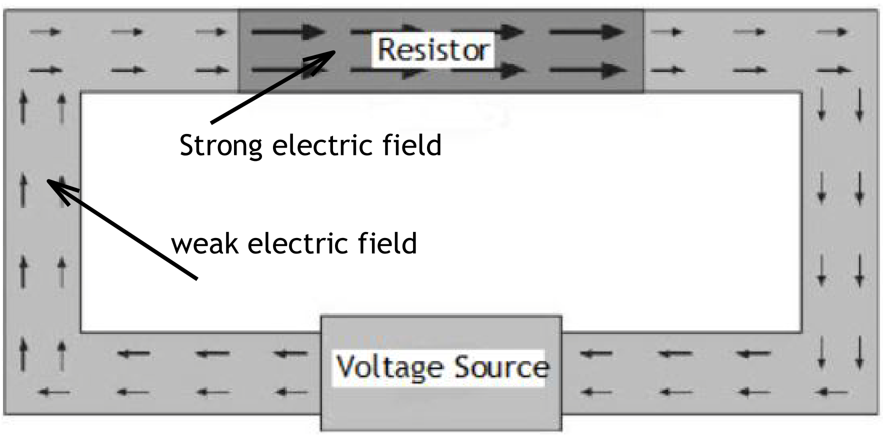

Figure 2*. Different Fields Inside the Conductor Wire and the Resistor*

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. What makes the electric field follow the curvature of the wire? According to Coulomb´s law the separated charges at the outlet of the battery can only cause a distance-dependent field (figure 3).

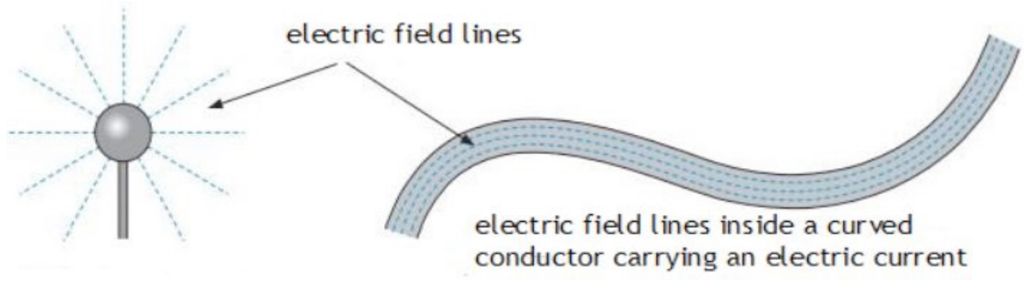

***Figure 3**. Spherically Symmetric Electric Field of a Single Charge Carrier ~ $1/r^2$ (left); Distance-Independent, Constant and Axially Aligned Electric Field Inside an Arbitrarily Curved Conductor (right)*

Test results showed (Haertel, 2005) that these and similar questions cannot be answered by the vast majority of our students 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. 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.

VOLTAGE AND SURFACE CHARGES

The solution to the didactic task presented here was in principle discovered over 150 years ago. In 1852 Wilhelm Weber pointed out that although a current-carrying conductor is overall neutral, it carries different densities of charges on its surface [Weber 1852]. Recognizing that a potential difference between two points along an electric circuit is related to a difference in surface charges the questions above can be answered.

Regarding the question of figure 1: The conductor sections at A and B in figure 1 have positive and negative surface charges respectively. Regarding the question of figure 2: In a conductor cross-section in front of and behind a resistor, in which the conductivity changes by many orders of magnitude, conduction electrons or positive charge carriers (positive grid ions) collect. The field associated with these charges drives the current through the resistor (fig.4).

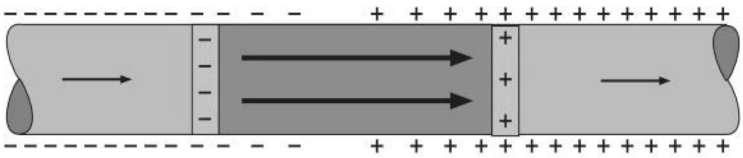

Figure 4. *Charged Separating Layers between Resistor and Conductor*

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 (figure 5).

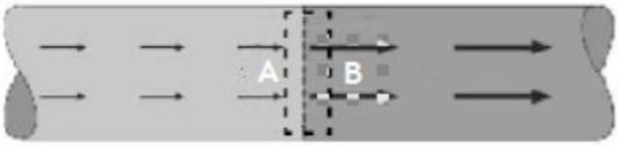

Figure 5. *Application of Gauss Law at the Interface between a Conductor and a Resistor*

If you place a cylindrical surface within a conductor and resistor such that the boundary surface is enclosed (shown as a dashed line in figure 5), the result is 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.

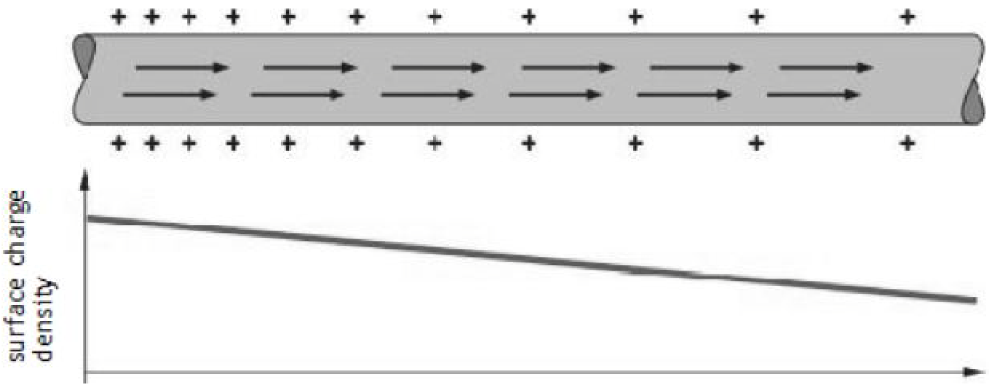

Figure 6. *Linear Gradient of the Surface Charge Density*

Regarding the question of figure 3: On the basis of Coulomb's law it can be deduced that an axially directed constant electric field is generated inside an infinitely long, straight conduct conductor if the density of the surface charges has a linear gradient (figure 6).

In the case of a curved conductor the gradient of the charge density deviates from linearity. More electrons accumulate on the outside of a curve than on the inside and thereby cause a curved and precisely axially aligned path of the drifting conduction electrons. The same applies in reverse for positively charged conductor parts (figure 7).

Figure 7. *Distribution of Surface Charges on Curved Conductors (Qualitative)*

Numerous references to the relationship between voltage and surface charges can be found in the literature [Marcus 1941], [Rosser 1963], [Sommerfeld 1964], [Haertel 1979, 1985], [Walz 1979] which, however, have obviously hardly received any attention within the scientific community. A detailed description of the historical development of this knowledge about surface charges as a self-evident fact of every current-carrying conductor as well as information on experiments for their detection and a detailed theoretical derivation can be found in previous studies (Assis and Hernandes, 2007).

INSTRUUCTION FOR CLASSROOM ACTIVITIES

Certain facts must first be taught if the concept of voltage or potential difference in connection with surface charges is to be introduced first and later quantitatively as energy per charge. In addition, particular learning steps are required, accompanied of course by appropriate demonstrations and classroom activities.

Charge, Coulomb Force

First of all, knowledge is required about the phenomenon of charge and about the type of interaction between charge carriers of different polarity. It must also be known that there are no additional charges inside a metallic conductor. A charged conductor only carries additional non-neutralized charge carriers on its surface.

Why the surface of a metal is a barrier for electrons is not easy to explain and must first be communicated as a fact. However, it can be stated that this barrier is not insurmountable. Inside the electronic tubes commonly used in the past, free electrons inside the tube were generated by heating a wire in a vacuum.

Function of a Voltage Source

Furthermore, it must be known that a battery or more generally a voltage source always has two metallic connections, and due to special forces, it has the property of withdrawing electrons from one connection and moving them to the other connection. In short: charges are separated. Depending on the type of voltage source, the forces, which are necessary for this operation are of different nature, such as chemical forces in a battery or electromagnetic forces in a generator; they are definitely no Coulomb forces.

The effect of these forces is always the same: There is an excess of electrons at one of the metallic outputs, the negative one. These additional electrons are missing at the other contact, the positive one. The solid lattice components of the metal appear at this positive contact as positive ions (figure 8).

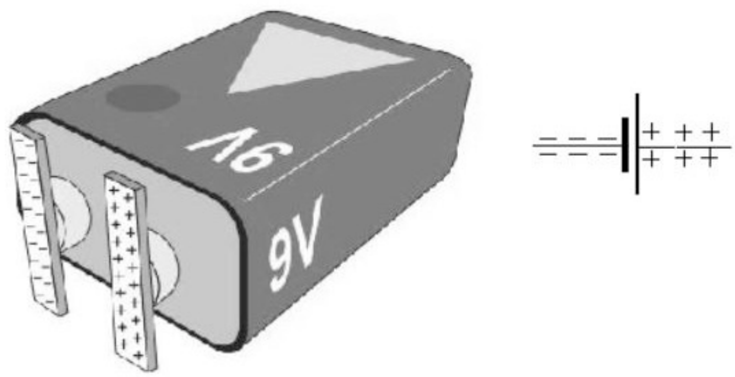

Figure 8. *A Battery as Voltage Source with Surface Charges on its Metallic Outlets*

The larger the density of negative respectively positive charges on the surfaces of the metallic contacts of a voltage source, the larger their mutual repulsion due to Coulomb interaction. Once a specific value is reached, which is characteristic of every voltage source, these Coulomb forces prevent any further increase in the density of additional negative and positive charge carriers. A state of equilibrium will be established, i.e., a steady state between the force of the voltage source and the restoring Coulomb forces.

Surface Charges on Conductors

If the contacts of the voltage source are connected with metallic conductors, this is equivalent to an increase in the surface area of these contacts (figure 9).

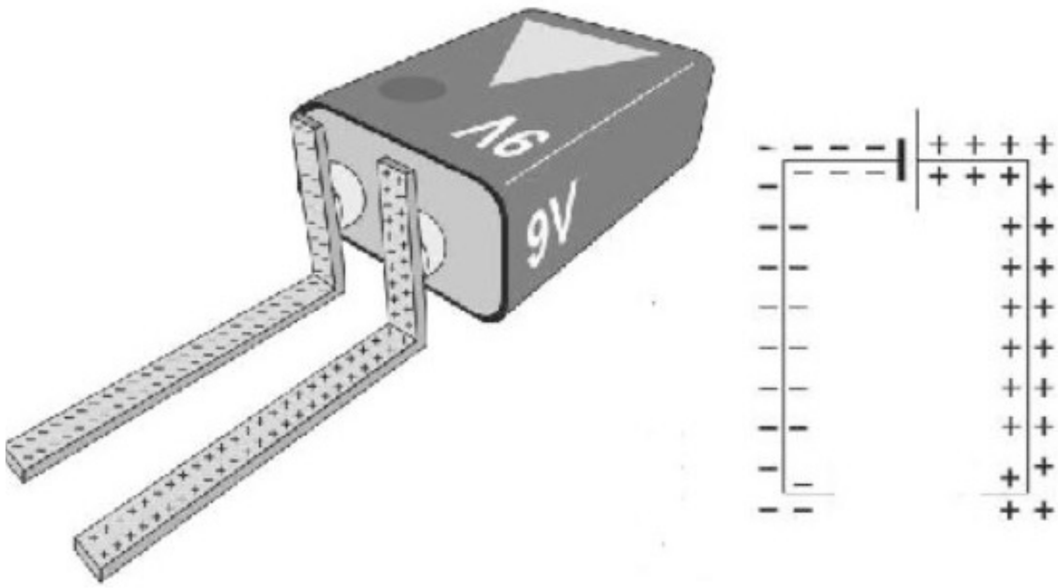

Figure 9. *Power Source with Connected Conductors and Surface Charges*

Due to the mutual repulsion between the charge carriers, the surface charges are distributed over this enlarged surface, their density being reduced for a short time. Thus, for this brief moment, the equilibrium between the non-Coulomb force of the voltage source and the Coulomb forces between the separated charge carriers is suspended in favor of the former. Additional electrons flow onto the enlarged surface until the density, characteristic of the voltage source, is reached and the balance of forces is restored.

Surface Charges within a Closed Circuit

If the external 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 so-called free electrons inside the conductors will take part (figure 10).

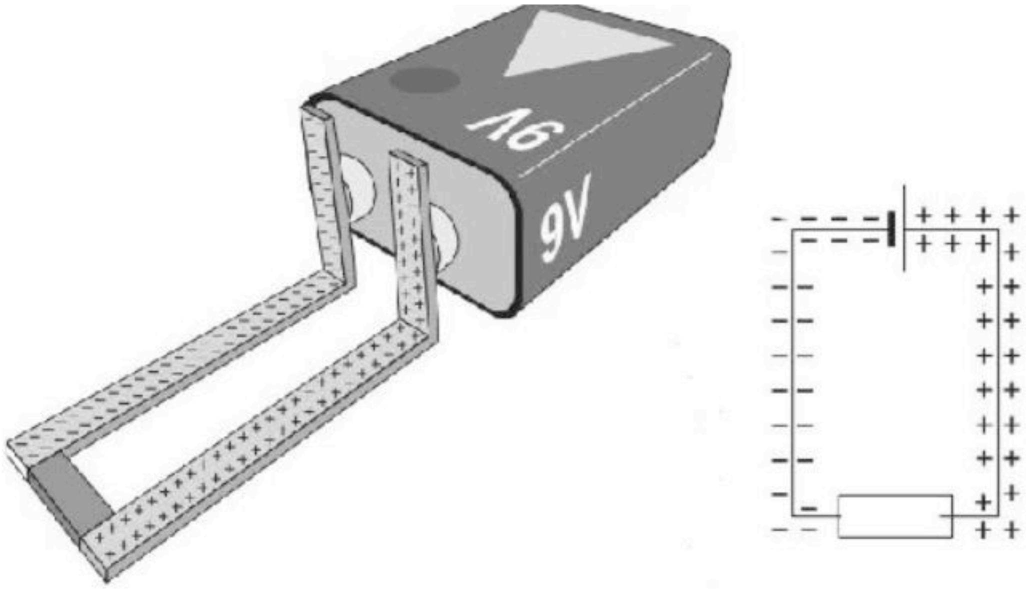

Figure 10. *A Closed Circuit and Surface Charges*

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.

Potential Difference and Pressure Difference in Water Circuits

A mechanical closed system of pipes in which water flows in a circle can be a good model for the electrical circuit. The advantage is that the flow and pressure conditions can be directly perceived in contrast to the electric case. However, in order to be acceptable as a model for the electric circuit, it must be required that the flow velocity of the water is as low as possible so that the kinetic energy of the flowing water is negligible, in analogy to the flowing free electrons inside a conductor. In order to still achieve a noticeable energy conversion, correspondingly large pressure differences must be assumed. Because of these conditions such systems are of no practical importance. They are primarily useful as didactical tool to explain the electrical circuit.

On such a model pressure gauges or better still water columns can be used to show the pressure conditions in series and parallel connections in order to transfer the results to the electrical circuit. This method was applied during the development of the IPN teaching unit (Haertel 1981; Haerman, 1982) on the electric circuit and supported by the following figures and experiments (figure 11):

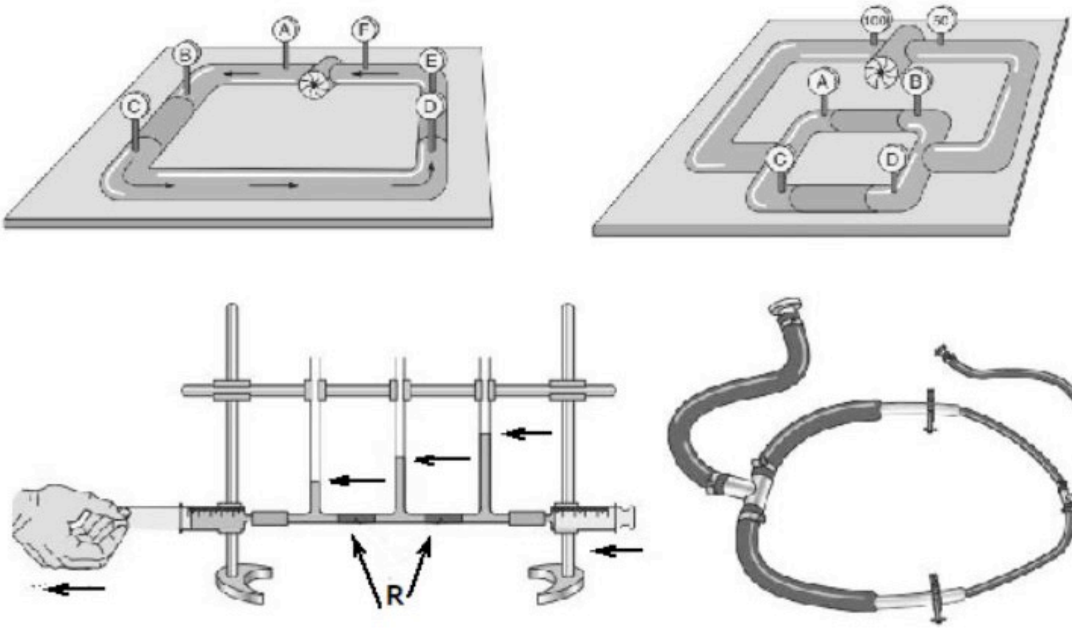

***Figure 11**. Figures and Instruments Used to Explain the Analogy between the Flow of Water and the Flow of Electrons*

Experience during the development of this teaching unit has shown that the water model is helpful to support the communication between teacher and students, in order to get an idea of the not directly accessible subject area "electric circuit".

However, our experience shows that one cannot expect too much from the analogy between pressure difference and voltage. This is also confirmed by earlier studies (Schwedes, 1995).

The different pressure inside a liquid is caused by its compressibility, i.e., by the fact that the liquid can be compressed to different degrees. This fact is usually not known to the students and it is certainly not enough just to communicate this fact. Rather, a very careful and demanding analysis is required to show the relationship between the pressure curve along a series and parallel circuit and the different densities of the water and to explain the conditions for a steady state.

If such an analysis is to be carried out, it can be helpful to mentally follow the start of a water flow as the front of a compression wave. If this wave front encounters a resistor, a jam will be formed for a short time, which triggers a returning wave. As a result, the further inflow is slowed down until an equilibrium between inflow and outflow is reached. In order for water to drain off permanently, the pressure at the output of the resistor must always be lower than at the input. This means that the water at the exit has a slightly lower density than at the entrance. It relaxes a little when passing through the resistor. The same thing happens with every additional resistor that the wave front encounters. The end result can only be a steady state if a pressure difference proportional to the size of the resistance has been established across each resistance.

The same analysis can be applied to the generation and distribution of surface charge in an electric circuit. The conduction electrons can be seen as a kind of "electron gas" that can be compressed or stretched by a voltage source, however, each time to a rather small degree.

However, the effect of the voltage source on the "gas of free conduction electrons" only shows itself in an accumulation or decrease of electrons on the surfaces of the conductors and not, as in the mechanical case of a water flow, in a change in density over the entire cross section. Due to short-range forces, water molecules only react with their closest neighbours and thus water can be compressed as a whole. Electrons are subject to far-reaching Coulomb forces. They repel each other rather strongly and can only be neutralized inside a metallic conductor by an exactly equal number of positive charges.

Demonstration of Surface Charges

As early as 1962, Jefimenko showed how the existence of surface charges in current-carrying resistors can be demonstrated with relatively simple means (Jefimenko, 1962). As resistors, strips of red ink were applied to a glass pane to which a relatively high voltage (> 10kV) was applied.

The display of an electric field outside and inside the resistor was made possible by scattered grass seeds, which align themselves according to the electric field (figure 12). Grass seeds are characterized by extremely fine tips at their ends, which, in the presence of an electric field, favors the formation of a relatively large dipole moment. In addition there is the small contact surface of grass seeds and the resulting low friction, which can be further reduced by vibrations on the glass pane.

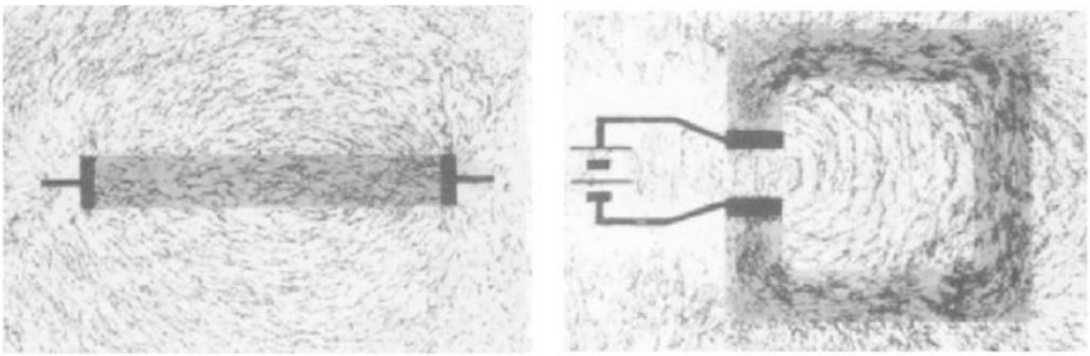

Figure 12*. Electric Fields Inside and Outside Differently Formed Resistors, Visualized by Scattered Grass Seeds (Jefimenko, 1962)*

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. A straw, hung in the middle on a long thread and with differently charged ends, moves in the vicinity of a current-carrying conductor clearly visibly under the influence of surface charges (figure 13).

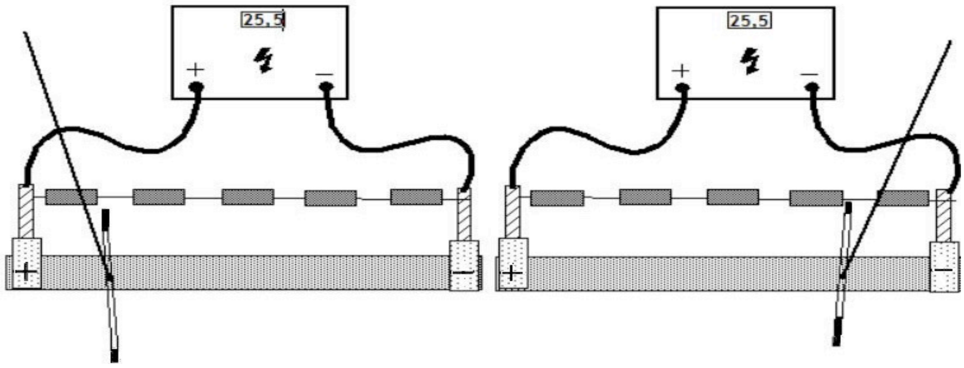

Figure 13. *Interaction between a Current Carrying Chain of Resistors and a Straw Charged with Different Charges at Both Ends to Demonstrate the Existence of Surface Charges (http://www.astrophysik.uni-kiel.de/~hhaertel/PUB/straw.flv)*

A successful course as challenge

In the U.S., a course on "Electric and Magnetic Interaction" has been published, where intensive use is made of the following pictures (Figure 14).

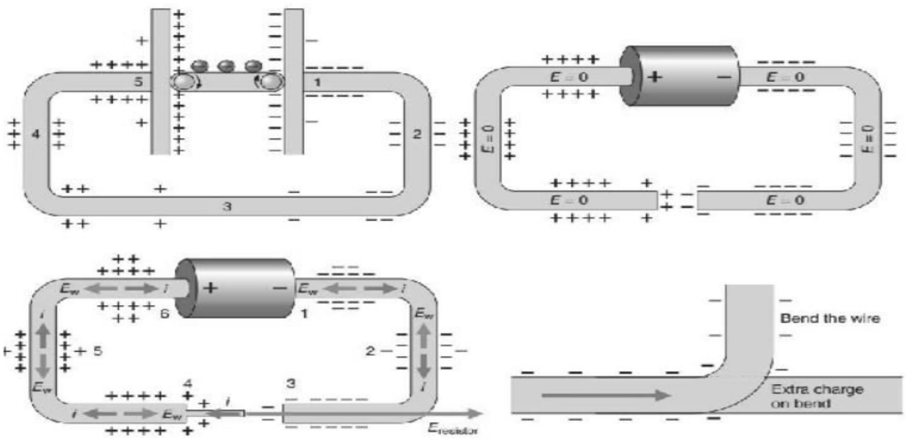

Figure 14*. Pictures From an American Course to Represent the Distribution of Surface Charges (Chabay and Sherwood, 2002)*

These pictures are used to explain some basic questions:

- What are the forces driving the electrons in an arbitrarily shaped conductor?
- What causes the strong electric field inside a resistor?
- Why do the flowing electrons follow every curve of the metallic conductor? etc.

Such pictures can 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.

CONCLUSION

The introduction of electrical voltage as „ability to do work“ and its quantitative definition as "energy per charge" is one-sided in its mathematical orientation. From a didactic point of view this approach is to be criticized as being too abstract and non-illustrative. It suppresses the connection between voltage and surface charges and thus deprives the students of the opportunity to reach a deeper understanding of this rather difficult term "voltage".

Unless the students do not ask by themselves what voltage actually is, they should be encouraged to ask such questions in order to stimulate a discussion about the existence of surface charges. In any case, such considerations should be part of a qualified lesson planning, so that the teacher can react appropriately to relevant questions.

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