The Electric Voltage

What do students understand?

What can be done for better understanding?

Hermann Härtel

1 Voltage and Electric Field

The term voltage belongs to the most difficult ones within the physics curriculum at lower and upper secondary level.

In contrast to the electric current, which can be related to moving electrons, the definition of potential or voltage as energy/charge offers no support for visualisation or insight.

Students at secondary level usually have not developed any other concept than mechanical particles in empty space, where interaction is linked with direct contact. So these students can hardly grasp the idea of voltage or potential difference between two points when there is no visible or even thinkable difference between these points. Because of this fundamental difficulty, all teaching efforts for students of that age are bound to fail when aiming at a deep and full understanding. All attempts which do not include an explicit and careful treatment of the field concept but which take support from mechanical analogies can only explain the effects in parallel and series circuits on the basis of plausibility, as in the following argument:

- If the pressure difference at the ends of parallel waterpipes is the same, why should not the voltage over two parallel resistors be the same?

It is this kind reasoning that can help to make things more familiar and plausible. A deeper understanding, however, cannot be reached by this method

2 Voltage and pressure difference in a water circuit

The term pressure, as force/area is in itself difficult and Area normaly regarded by students as a special force in a certain direction (opposite to pull). Moreover, the pressure along a water circuit is a complex function of different parameters. The question is whether this analogy can be helpful while teaching electricity and especially voltage, when it is so difficult in itself?

Our experience has shown that this difficulty can be reduced by the following means. First we take as analogy a closed water circuit under high pressure but with a very low flowing rate.

Figure 1: Representation of a water circuit

This latter condition is not only necessary to avoid any turbulence and to simplify the pressure measurements along the tubes. It is also necessary to make the analogy to the electric circuit as close as possible. Fast running water has kinetic energy which has to leave the system when the waterflow is switched off. The kinetic energy of electrons, however, is negligible compared to all other interaction processes. So a current can be switched off with almost no energy dissipation.

There is a second possibility to simplify the teaching of pressure in a water circuit: The introduction of flexible tubes.

In the unit on “Current, Voltage, Resistance” of the IPN Curriculum (1981) we have used the picture of a water circuit where the tubes were rather flexible and where the differences in pressure could easily be observed.

These pictures have proven to be quite fruitful in discussing pressure measurements along a water tube. In particular, the students could be convinced that the pressure along the tube, connecting the pump and the resistor, is (nearly) constant. This finding is a big step because in many cases the students are convinced that the pressure at the entrance of the resistor is much higher than near the pump.

3 Surface charges in electric circuits

The difficulty connected with the understanding of the term voltage can be demonstrated with a rather simple question:

Why do I measure a voltage across a resistor - point A and B - and practically no voltage between point B and C? The three cross-sections seem to be identical on a microscopic scale. The same amount of electrons with the same drifting velocity are passing through as follows from Kirchhoff’s first law. Most textbooks explain that there is a potential difference between these two points. But what corresponds to this difference in microscopic dimensions? There is even the same electric field and in a super-conductor this field is even zero. This problem is, of course, not one of the physical theory. The problem is that many teachers and high school students cannot give a satisfying answer to this rather simple but basic question.

It is an astonishing fact that physics education has overlooked a rather simple explanations for this question: the existence of surface charges, accompanying any current flow within a conductor. The existence of these surface charges are described in some textbooks and in some articles. In most cases, however, they are not mentioned. The reason for this lack of attention to an existing physical phenomenon may be found in the fact that these surface charges are rather small and normally not detectable. The loyalty to the principle that only measurable terms are allowed to enter physical theories may have led the teachers and textbook writers to look only for the drifting electrons within the wire and to declare the distribution of these moving electrons uniform and neutral.

It is proposed in this article to change this attitude and include a complete study of all effects connected to surface charges into the curriculum of electricity, especially when the term voltage is treated.

This proposal does not mean, that this new topic has to be taught to all students at lower secondary level. The lack of a field concept, as it was mentioned at the beginning, is again a severe barrier in understanding the behaviour of charges, their mutual interaction and their effects over long distances. However, the study of these surface charges seems to be necessary for physics students and teachers for at least two reasons:

- It may help to clarify their own ideas about voltage, potential, etc.
- It may show teachers the complexity of the so-called simple electric circuit” and may lead to more careful and adequate teaching with better anticipation of the existing difficulties in learning and understanding.

And last but not least, there may be some students who really want to know more about voltage and potential and who will not go on without a satisfactory answer. In this case details about surface charges and their influence on all the other parts of the circuit may give substantial support in encouraging further studies and in creating or maintaining curiosity.

4 Proposals for teaching_material

The theoretical background about surface charges and electric fields around a current-leading conductor has been treated in textbooks, for example in Rosser: Classical Electromagnetism via Relativity (1968). They have been re-discovered and further developed by Walz (see his article in this publication). Therefore the following remarks do not intend to give a complete and exact representation of the phenomenon with the best fit to all existing theories. The interested reader is referred to the above mentioned publications.

The pictures and explanations that follow intend to give an initial and simple demonstration of the discussed phenomena as they could be presented to teachers, students or others. In any case they have to be developed further. It has to be stressed that these pictures are exaggerating a very, very small effect, as can be seen by the following calculation:

If one calculates the extra surface charge at the edge of a conductor, which is necessary to reflect a current of 10^{19} electrons per second at an angle of 90^{o} the result is abut 1 single electron.

The ratio 1 to 10^{19} is negligible in praxis but not in theory because without this single electron it could not be understood why the movement of the electrons forming the main current is reflected by 90^{o}.

For the demonstrations of surface charges along simple electric circuits we have developed some simple pictures to start the discussion and to support individuals' own thinking. These pictures can be drawn on transparencies or on a computer screen. The latter method is more comfortable because it allows individualization and it is easier to handle.

In the following, all effects corresponding to interaction of surface charges on different wires (electrostatic induction) and geometrical conditions like curved wires etc. are neglected.

First it has to be pointed-out that a normal copper lead consists of an equalized amount of positive and negative charges (figure 6 a) .

Figure 6:

a) A resistor with leads without a current

b) Representation of a resistor with leads with and without surface charges

Surface charges connected with a current flowing through a resistor are symbolized as shown in fig. 6 b.

For a circuit with resistors in series or parallel the distribution of surface charges for steady state coditions can be symbolized as follows:

As Walz has shown-(see his paper in this proceeding) a surface charge distribution according to c=C + C-x 0 renders an axial and homogeneous electric field within a straight wire, where x is the coordinate in the direction of the current.

Fig 7: Change in the distribution of surface

According to the change in conductivity in the copper wire and the resistor, the constant c is changing, giving a different gradiant in the surface charge distribution and therefore a different field within the copper and the resistor.

It may even be helpful to consider the process which builds up these extra charges on the surface of a wire and on the resistor after the battery is connected to the circuit (see fig. 8) .

Neglecting any transient effects due to electrostatic induction one has in the very first moment a nonaxial electric fiLeld in the wire. This field will cause some electrons to move to the surface until the electric field is bent to the cial direction. Due to the small gradient in the distribution of the surface charge, the axial field within the copper lead is reduced to the steady state value (according to $j = E \sigma$)
Volumes charges within the region where the conductivity is changing (dotted area) are neglected to simplify the representation.

Again it has to be stressed that these pictures are exaggerating and simplifying a rather small effect. But this small effect together with the field concept is necessary for understanding. Having reached this point the students should quite easiliy rely on Ohm’s law and Kirchhoff’s law for further studies for this should make their work easier and more effective.

References:

SOMMERFELD , A. Elektrodynamik Leipzig 1964, 113-117

BERGMANN-SCHAEFER Bd. II: Elektrizitätslehre

HÄRTEL, H. Zur Einführung des Spannungsbegriffs in der Sek. I, in (HÄRTEL, Hrsg.): Zur Didaktik der Physik und Chemie. Schroedel, 1979,
WALZ, A. E-Felder um stationäre Ströme, Der Physikunterricht 2 - 1984, 61-68
ROSSERt W.G. Classical Electromagnetisme via Relativity. Butterworths London 1968.

COMBES, C.A. and LAUE, H. Electric fields and charge distributions associated with steady currents. Am.J.Phys. 49, 1981

5 References

[1] Sommerfeld, A., Electrodynamics (Academic press, New York, 1952), 125-130
[2] A. Marcus, The electric field associated with a steady current in a long cylindrical conductor, American Journal of Physics, 9, 225-226 (1941)
[3] Jefimenko, O.: Amer.J.Phys.30, 19-21(1962),
[4] Rosser, W.G.V. What makes an electric current flow, American Journal of Physics, 31, 884-885 (1963)
[5] Härtel, H.: The electric voltage: What do students understand? What can be done to help for a better understanding? In: Duit, R. (ed.); Jung, W. (ed.): Rhöneck, C. von (ed.): Aspects of Understanding Electricity. Proceedings of an International Workshop. IPN-Arbeitsberichte 59. Kiel: IPN, 353-362, (1985)
[6] Härtel, H: A Qualitative Approach to Electricity. Palo Alto: IRL, IRL Report. IRL 87-0001, 111 pp. (1987)
[7] Härtel, H.: Spannung als Ladungsunterschied, Naturwissenschaft im Unterricht Physik/Chemie, Heft 31, 36-38, (1988)
[8] Moreau, W.R. Charge distribution on DC circuits and Kirchhoff’s laws, European journal of physics 10, 286-290 (1989)

[9] Chabay, R., Sherwood, B. Electric & Magnetic Interactions, New York, John Wiley (1995)