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The Electric Circuit as a System: A New Approach

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Summaries

English
In this new approach to the presentation of the electric circuit, the three fundamental terms current, potential difference, and resistance are introduced simultaneously in a qualitative way, using the system aspect of the electric circuit as an integrative base while starting from the individual knowledge and the conceptional schemes that students bring into the classroom.
This approach is in contrast to the traditional one, where the single terms are introduced in a linear sequence, according to the structure of the discipline and based an measurement operations.

Deutsch
In dieser neuen Konzeption werden bei der Behandlung des elektrischen Stromkreises die drei Grundbegriffe *Stromstärke, Spannung* und *Widerstand* gleichzeitig in qualitativer Weise eingeführt. Der Systemaspekt des elektrischen Stromkreises dient dabei als integrativer Rahmen, wobei von den Vorstellungen und Schemata, die die Schüler mit in den Unterricht bringen, ausgegangen wird. Dieser Ansatz steht im Gegensatz zu dem traditionellen Vorgehen, bei dem die einzelnen Begriffe in einer linear aufbauenden Abfolge entsprechend der physikalischen Sachstruktur und auf der Grundlage operativer Meßverfahren eingeführt werden.

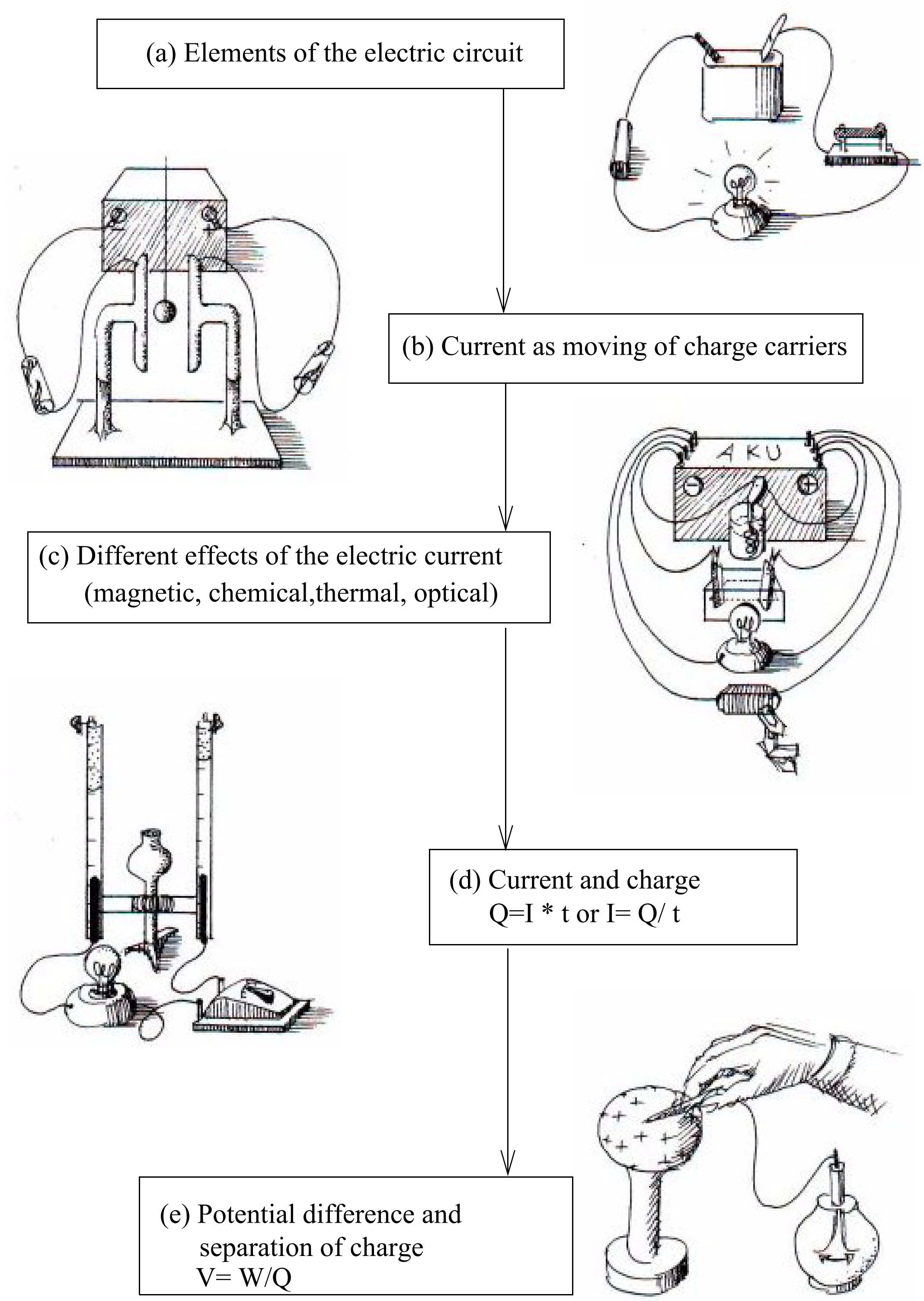
Francais
En traitant le circuit électrique, on introduit les trois termes fondamentals *courant, tension*, et *résistance* en meme temps dune facon qualitative. La structure du système "circuit electrique" sort comme base intégrative ou on départ des notions et concepts des étudiants qu'ils emènent dans le cours. Cette approche est contraire au cours traditionel où les trois termes sont introduits dans une séquence linéaire selon la structure de la discipline et basés sur des opérations des mesure.

1. Characteristics of the traditional way of teaching this topic in German schools

If one analyses some new school text-books[1] in relation to the development of the various important terms and topics belonging to the theme "the electric

1.See, for example, the following texts: *Natur und Technik*, Sekundarstufe 1 (1976) (Cornelsen-Velhagen und Klasing: Bielefeld), GROSS-BERHAG (1976), Physik, Sekundarstufe 1 (Ernst-Klett Verlag: Stuttgart), and HÖFLING (1975), *Physik-Band 1*, (Dümmler Verlag: Bonn).

circuit", one finds that more or less the same sequence is used. This may be represented by the scheme shown in figure 1.



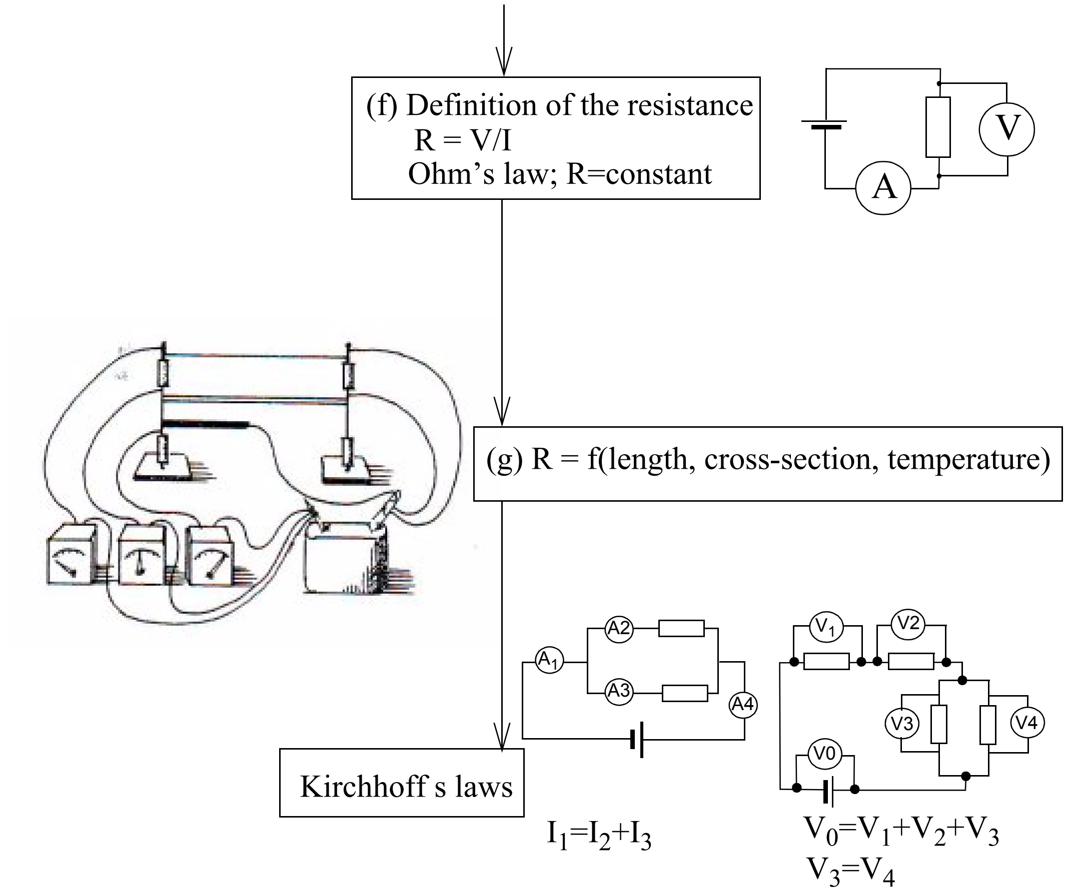


Figure 1. Teaching sequence about the electric circuit

In this sequence, the intention is to represent the result of physics as a linearly growing sequence of terms, definitions and rules. Although the teaching starts with the representation of the complete circuit, the interest is immediately concentrated only on the current and its various effects, e.g. magnetism, electrolysis, etc. After defining "charge" as $Q = I \cdot t$, the force between separate charges is studied. From electrostatic considerations the definition

$$V=W/Q \text{ (work per transported charge)}$$

is derived and applied to the dynamic case of an electric circuit to characterize the energy source or battery. After that, measurements on resistors show that the ratio of V and I remains constant and V/I is then introduced as a definition of the resistance. Some effort is made to explain the difference between this definition and the fact that for some material (metals), and for T=constant, the resistance is constant.

This linear sequencing with its hierarchical structure is problematic in several ways. The sequence I-->Q-->V-->R is a construction which does not reflect the way in which knowledge developed in science. Moreover, it shows only the surface of a more complex and interdependent connection between these different terms. There is, for instance, no obvious or simple argument to show that the result gained from electrostatic experiments also holds for the dynamic case of the electric current. Finally, such a linear sequence is problematic for a learner, if he or she really is to achieve an understanding of the electric circuit. For example, if a voltmeter is used which relies an Ohm's law for the measurement of the voltage, how can one find anything other than the fact that Ohm's law is true?

A thorough discussion of the question of *what* learning and understanding of physics can be achieved when it is presented in such a linear and hierarchical sequence, requires more than just one example of the type given. Such a discussion is, however, very difficult because it touches upon some deep convictions about the function and structure of physics in general and about what is meant by learning and understanding. Therefore, it is proposed first to illustrate an alternative approach, where this linear structure is exchanged for a system approach. Thereafter, the discussion about linear sequences in physics will be taken up again. Before presenting this alternative approach, a second characteristic of the traditional method has to be mentioned. This is the strong dominance in our teaching of the measurement operation, as is seen from the way terms like *current*, *potential difference*, and *resistance* are introduced. This is especially obvious in relation to the concept of resistance which is introduced as R=V/I. The question is what is to be understood by the equality sign "=" or by the expression "R is defined as V/I"? What is the meaning of this for the learner?

Obviously, the right side and the left side of the equation are not equal in all aspects. The resistance as a description of a special part of reality is concerned with charge carriers, their mobility, and their interaction with regularities or irregularities within the material. Potential difference is concerned with electric fields, charge and energy. The equation R=V/I is not just a full definition of the left side (through the right side). It is a creative law which fits reality and which can simplify and unify the description of it. And it is, of course, at the same time a method to define the unit of R by a measurement operation. If this last aspect is dominant, or if it is the only one in the process of presenting the facts to a learner, it may be suggested that the underlying epistemology is related to operationalism or behaviourism. If one can only describe what one can observe, then a term in physics is only connected with or defined by a measurement. According to the development in the field of epistemology, such a position seems to be questionable. An alternative for presenting the results of physics, in which not only the empirical data but also rational parts of knowledge are explicit, is shown in the following. In the light of this alternative, the criticism expressed above should become clearer and easier to understand.

2. Reasons for a new concept

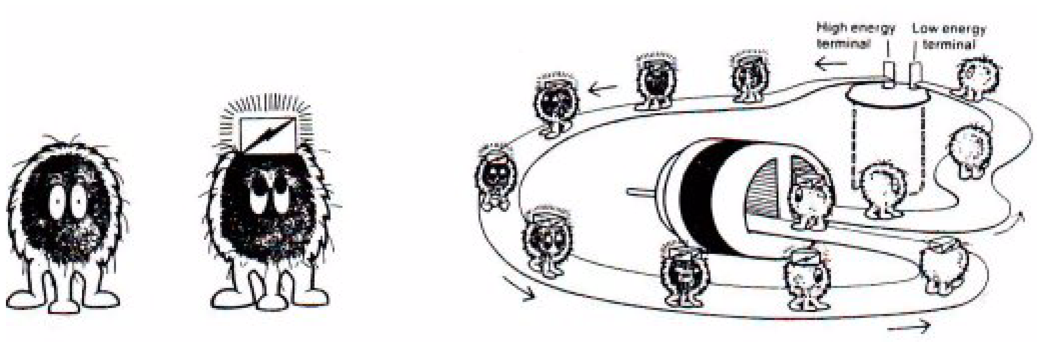
2.1. The importance of students' individual knowledge and conceptions

One important reason to start thinking about the traditional way of teaching was given by studies of students' learning in the field of electric circuits. As Maichle (1979) and also Rhöneck (1980) have shown, the effectiveness of science teaching in this field is rather small if one neglects the test results obtained immediately after the teaching period. It was shown that students come with certain conceptional schemes into the classroom or at least with the ability to react in certain ways by solving a problem. These schemes, wherever they may come from, are often very different from the ideas and concepts developed by science and presented in the classroom to be learned and understood. It seems to be very important for successful teaching to know these conceptional schemes already present in the learner. Otherwise, teaching may result in producing two separate concepts, one for daily life and one for the physics classroom. To exemplify this, we may refer to the notion of "consumption of electricity". In its everyday use, the term *electricity* implies some form of primary energy, like petroleum, coal and gas, and its "consumption" is evident. In the context of physics education, the students learn that current (as a measure of the flow of electricity) remains constant before and after it passes through a resistor (the "consumer" of electricity). Usually, these two ideas remain separate, and contradictions are overlooked or suppressed. In the long run, the daily life concept will dominate. Successful teaching should start with those concepts which pupils already hold or develop. By showing them convincingly that there are limits, contradictions and ways for further development of their concept during the teaching that follows, the pupils' adherence to these everyday concepts may be overcome.

2.2. Linearity or system?

A model from an American Curriculum (ISCS 1970) presents an idea of electrical energy like a package carried by independently moving single particles which is then consumed. This analogy is well known in teaching and is depicted in figure 2. In this model, attention is focused on single particles whilst the relation between them is not considered. Moreover, the energy is materialized and consumed. The problematic nature of this concept becomes apparent when the following questions are raised:

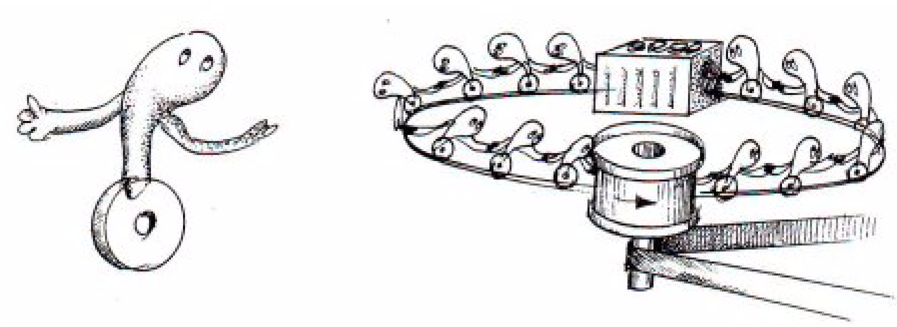
- Will the particles keep the same distance or will there be a congestion just before the resistor?
- Will all particles stop when the circuit is broken at some point?
- What happens to the energy in the supply leads when the circuit is broken?
- Why does the current divide at any branching according to the value of the resistances that follow?



(a) (b)

Figure 2. (a) Electroparticle without and with energy
(b) Model of an electric circuit

If this kind of model is to be accepted at all, the version shown in figure 3 offers a better foundation for a development free of contradictions. In it, the particles cannot move autonomously but are driven by the battery. Thus, the interrelation between the particles - the system aspects - becomes visible and all the above questions can be answered in terms of this model in line with experiments.



(a) (b)

Figure 3. (a) Electroparticle (b) Model of an electric circuit

As a consequence of these considerations, it is advisable to talk right from the beginning of the teaching sequence about single terms like current and resistance, and at the same time about the complete system. Both aspects are then continuously broadened and specialized.

For the electric circuit as a system, a structure may be developed which is symbolized and explained in the following way (figure 4).

The electric circuit consists of three essential elements: (i) the drive, (ii) a flow of matter in a closed format and (iii) a hindrance (obstacle). Through the drive, energy is transferred from the outside into the system, and through the hindrance it is removed from the system.

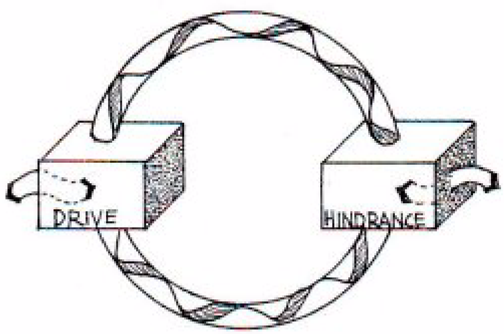


Figure 4. The electric circuit as a system

Another argument for the importance of the system approach can be drawn from the fact that there are two rules (by Kirchhoff) to describe the complete electric circuit.

The first rule

$$\sum I_i = 0$$

describes the conditions for a single point.

The second rule

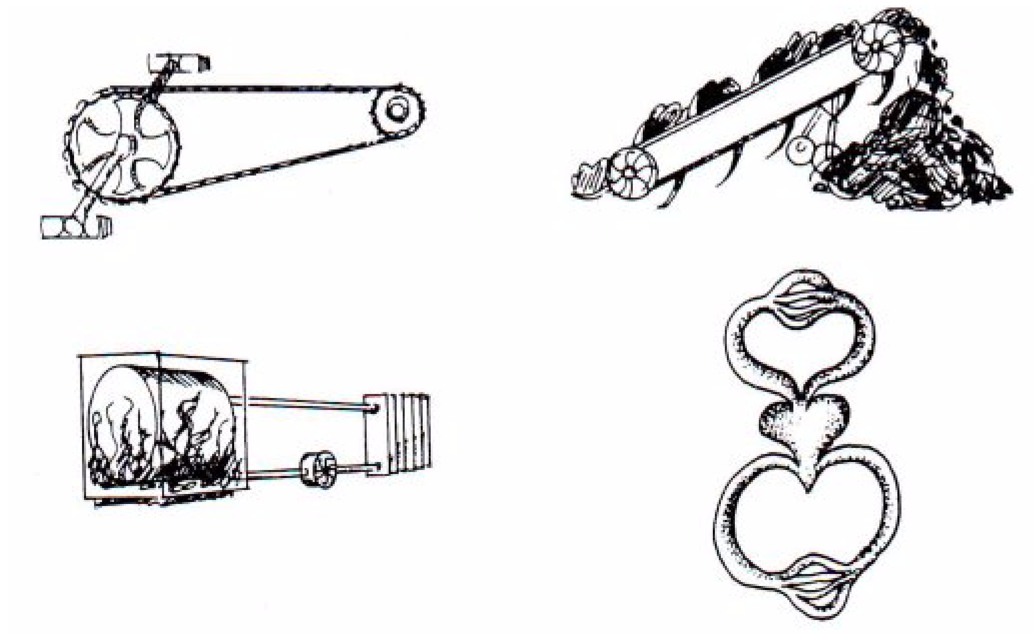
$$\sum V_i = \sum R_i \cdot I_i = 0$$

describes the conditions for a complete network. Both descriptions have to be considered at the same time to give a correct representation. The traditional way of teaching, however, has the tendency to stress only the consideration of single points. The consideration of a complete system can only occur at the end of the teaching sequence.

3. Representation of the IPN teaching unit

3.1. Consideration of alternative systems

At the beginning of the teaching sequence, the more general question about the possibilities of transporting energy is raised. The importance of this question can be made clear by giving an overview of the historical development of the production and transportation of energy (from working animals and slaves to steam engines to the electric networks). When considering different technical solutions of transporting energy, it is important to present some systems where energy and matter are consumed (e.g. transportation belts, blood circulation) and some systems not involving the consumption of matter (e.g. transmission belt, central water heating system). Some examples are shown in figure 5.



(a) no consumption of matter (b) consumption of matter and ener

Figure 5. Energy transporting systems

Looking at figure 5a the student can see that matter does not necessarily have to be consumed although the flow of matter is necessary for the transportation of energy. In the light of this information, the assumption becomes questionable that an electric current, as a flow of material within an electric circuit, is consumed. Moreover, we may demand that this question has to be decided by an experiment. To which kind of system (consumption or non-consumption of matter) does an electric circuit belong?

To answer this question by experiment, the term "flow of matter per time interval" has to be developed. This is a first step for introducing the term *current* (in German, *Stromstärke*). With the help of an ampere meter it can be shown that there is no difference in current before and after a resistor. Therefore, the electric circuit appears to have a structural similarity with the systems (bicycle chain, heating system) shown in figure 5a. The question then remains how one can decide between a system like the transmission belt or bicycle chain and a system like the central water heating. In the first of these, energy is transported in the form of a directed force. In the second, energy is transported together with the fluid in some kind of "internal" energy. A possibility to decide to what type of system the electric circuit belongs, arises from a consideration of the speed of the transported energy, compared with the speed of the flowing material. The influence of the difference in length of the supply pipes can also be taken into account. In a system like the transmission belt, the speed of the belt is not related to the speed with which the energy is transported. As soon as the system moves, the energy is reaching the consumer. In the heating system, however, the transport of energy is directly linked with the flow of water. Doubling the length of the supply pipe will double the time between switching-on of the circuit and the result at the radiator. Reversing the rotation of the flow is only possible with rather long retardation. Again, the length of the supply pipes will have a strong influence.

As a result of these considerations and as the basis of appropriate experiments, the structural similarity between the electric circuit and the system of a bicycle chain, a transmission belt, or a circular pressure pipe system can readily be established. This structure may always be considered analogous to the examples of the electric circuit. Thus, the students are repeatedly given the opportunity to revise their old conceptional schemes and to establish the new one (see figure 6).

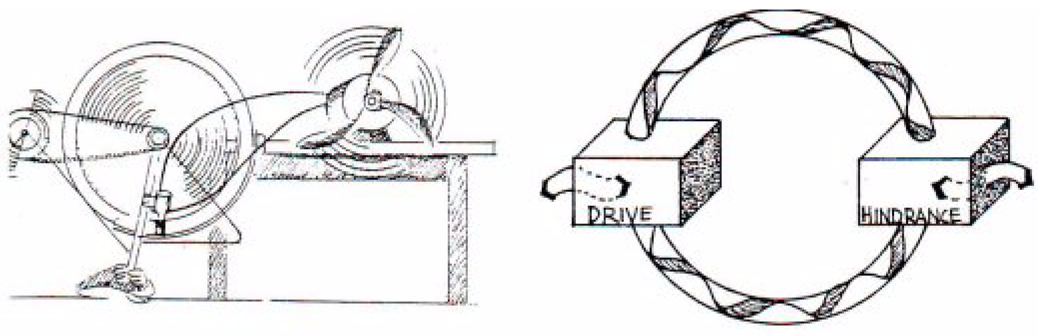
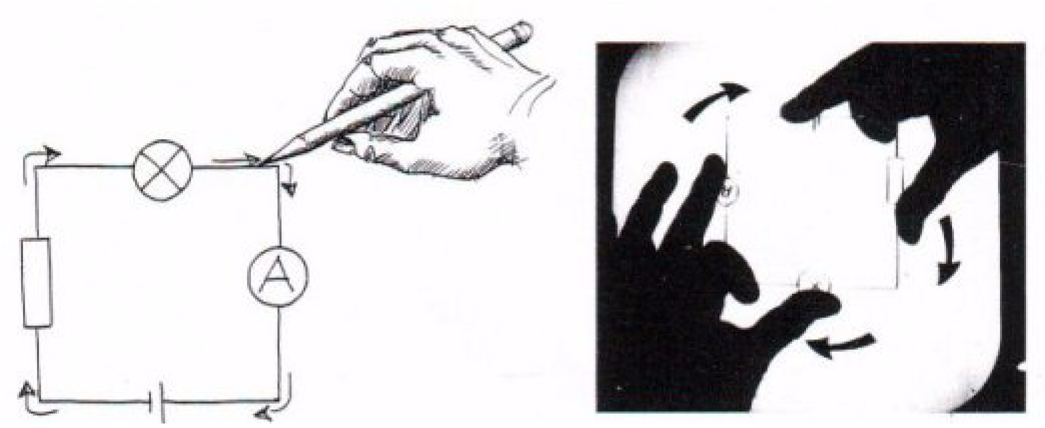


Figure 6. Electric circuit and structure

In accordance with this, the teacher should avoid presenting the flow of the electric current (from + to -) by following the circuit from one point to the other. Instead, he should always emphasize the movement of the whole "ring" of electrons (figure 7).



(a) movement of a point (b) movement of a circle

Figure 7. Movement of electrons

3.2. How to introduce the term "voltage" or "potential difference"

The term voltage is introduced in close relationship to the concept of *drive* for or cause of the motion. An in-depth study of the interaction between the electric field and the charge carriers is not attempted, because students of that age are unfamiliar with the concept of a field. Although it may seem inconsistent that the magnetic field is treated without further ado whilst the motion of an electric field seems too abstract, we have to admit that a concept of the electric field cannot be presupposed. Therefore, the term voltage is introduced as an analogy to pressure difference being the cause of the flow of water in a water cycle. In doing so, the term pressure is treated only qualitatively.

3.3. The introduction of Ohm's law

If it is understood that the electric circuit is a system consisting of the three elements, viz. the *drive*, the *closed flow of matter* and the *hindrance* (obstacle), the transition to a quantitative treatment can be facilitated by explaining the process as a dynamic equilibrium. If the stationary flow of electricity is interpreted as the result of a dynamic balance between drive and hindrance, the following semi quantitative relations follow immediately:

- The stronger the hindrance, the smaller the flow (if the drive remains constant).
- The stronger the drive, the stronger the flow (if the hindrance remains constant).

When proceeding to a quantitative definition of terms, it is possible to discuss with students the question under what conditions two completely different resistors from different materials can be regarded as having the same resistance. One can also ask the question under what circumstances it can be concluded that the resistance of a resistor remains constant whilst the electric current is changing. If the students accept that the resistance is not a fixed term but that it can be different at different temperatures, or for different velocities of the moving particles, etc., the condition that doubling the drive gives twice a current is a very simple and understandable answer to this question. Ohm's law V/I = constant or R = constant can be presented in this way as a very simple and reasonable hypothesis which has to be proven or refuted by experiment. Further details of this approach are given in the IPN teaching unit (Härtel 1981).

4. Some remarks on the topic "alternating current" (generator, transformer)

4.1. Electromagnetic induction

A teaching unit for this area and related topics is under development and will be published in 1982. The relationship between alternating current and the ideas described above can be seen from figure 8. In treating electromagnetic induction, the interaction between the turning magnet (the change of the magnetic field) and the "ring" of electrons within the coil and within the complete electric circuit is introduced to explain the observed phenomenon (generation of the alternating current).

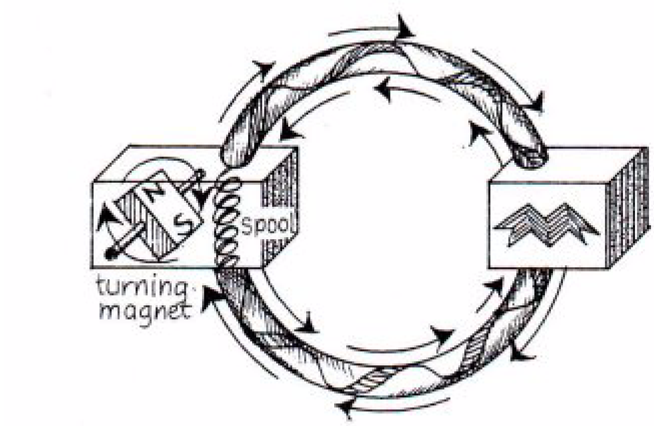


Figure 8. Generation of an "alternating current"

4.2. Transport of electric energy transformer

For this topic, the treatment of the electric current as a closed "ring" of electrons is extended according to the following picture (figure 9).

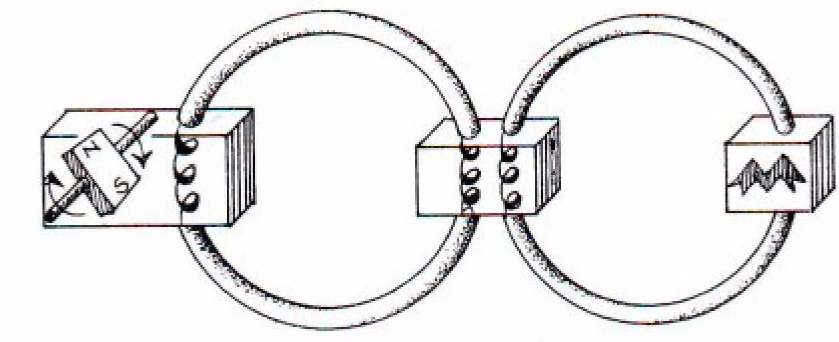


Figure 9. Transformer

The function of the transformer can be treated as being analogous to the mechanical transmission of a large movement with a small drive to a small movement with a strong drive. Both involve the concept of conservation of energy. When talking about long-distance transmission lines and power stations, the single processes can be put together to give a complete picture by connecting the consumer and the power station through three magnetically coupled "rings" of electrons which render possible the flow of energy (figure 10).

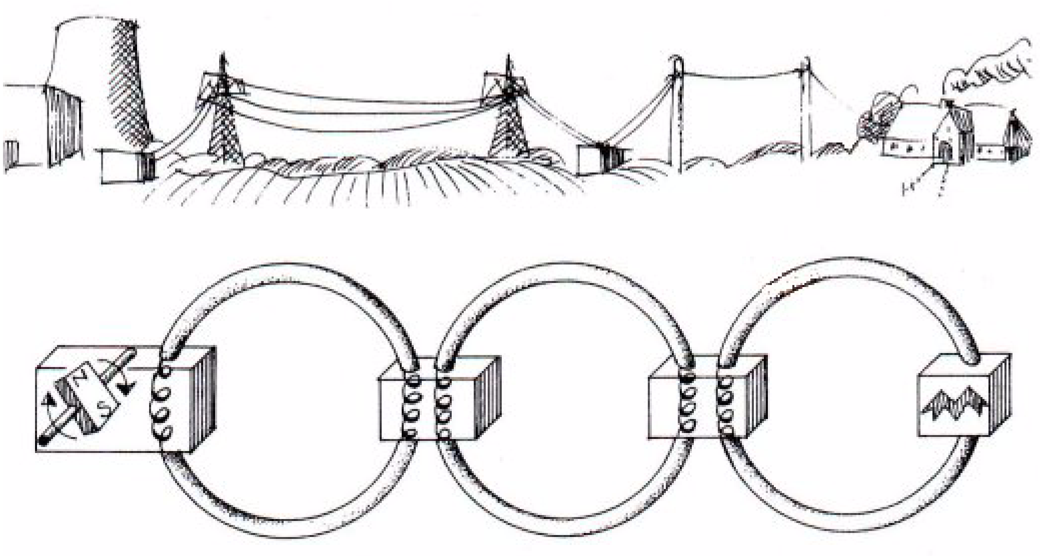


Figure 10. Long-distance transmission line

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