The Electric Circuit - A System Approach

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ABSTRACT

The traditional treatment of the electric circuit in textbooks can be criticized in at least three respects: A) Knowledge of the global aspects of the electric circuit as a system is essential for a deeper understanding. However, this is not sufficiently emphasized. B) The presentation of the term "potential difference" or "voltage" as energy per charge is too abstract, without reference to surface charges that are always present. C) The treatment of the electric circuit, based on Ohm´s law and Kirchhoff´s rules, is exclusively based on stationary states, without including the ever-existing transition processes. This article concentrates on the global aspects of the electric circuit as a system and its importance for a deeper understanding; it also provides detailed information for corresponding classroom activities. The other two critical points are treated in subsequent articles.

Keywords: Electric circuit, sequential thinking, system thinking, models for the electric circuit, role playing game.

INTRODUCTION

If newcomers are introduced to mountain climbing with the aim of mastering the more demanding parts of this activity, it is essential that the degree of difficulty be chosen carefully. If it is unreasonably high, failure during climbing can trigger a vicious circle, where doubts about personal performance increase the probability of future failure. On the other hand, if the degree of difficulty is too low, the novice climber may regard the exercise as meaningless and not worthwhile.

The goal of training should be that every member of the group will reach the summit with a sense of pride and satisfaction about one´s own performance. This individual experience of success, bringing with it an enhanced belief in one´s own ability, may create a long- lasting interest in climbing. If the task is too simple, the climber may lose his initial desire and decide instead to pursue other kinds of sport.

There are parallels in a physics classroom. Alpine climbing is regarded as difficult, demanding and potentially dangerous; physics may be viewed in much the same way as a very important topic in the school curriculum, and yet the most difficult one. Success in a physics examination is a cause for celebration, but failure may generate a feeling of personal incompetence.

The selection of a suitable degree of difficulty is therefore as vital in physics as it is in climbing. If the requirement of a physics student is the mere learning by heart of facts or the manipulation of a few specific equations - for instance Ohm´s law and Kirchhoff´s rules - without the need for a deeper understanding, the student may lose interest and have little motivation to pursue the subject further.

Similarly, if the course content is presented in an abstract or mathematically demanding manner, students may be overwhelmed. If failure is more likely than success the negative impact on students and their ability to learn may be considerable.

If only stationary states are presented when dealing with the electrical circuit without mentioning transition states, the chance is wasted to stimulate the students to think deeper and more precisely. Without such dynamic transition processes stationary states are less attractive and corresponding tasks can often be mastered without deeper thinking.

In relation to the electrical circuit the results of learning research over the past 30 years show that the set of learning goals - the desired summit - are not achieved by most students (Wiesner 1982. v. Rhöneck 1982).

Even students with high grades in physics exams, when confronted with slightly modified problems, often approach the revised problem on the base of the same misconceptions they held before, rather than making use of the principles presented in the classroom (Driver, 1985; McDermott and Shaffer, 1992).

Over the years great efforts have been made to investigate these misconceptions and to develop processes for their development towards physical principles and models (diSessa

1993; Müller, 2004). However, most students fail to meet the learning goals set by their teacher. For example, the well-known misconception about consumption of current is robust and persistent (Slater et al., 2001).

According to the opinion presented here, one reason could be the uniform way in which the subject matter is presented in traditional textbooks. The definition of the level of difficulty is partly too low, partly too high. In addition, the subject matter is offered incomplete. The subject matter is too simplified by a lack of emphasis on the system aspect of the circuit. The content of the lesson becomes too abstract through the exclusive treatment of the central term voltage or potential difference as energy per charge (V=E/q). Lessons are incomplete that deal exclusively with stationary states without indicating the necessary existence of transition processes.

In three sequential articles these comments will be amplified, illustrating some major deficiencies that are found in traditional textbooks. These articles also explain some possibilities and didactical measures to help organize and support the learning tasks necessary to reach a deeper understanding of this rather complex phenomenon, the “Electric Circuit”.

THE ELECTRIC CIRCUIT AS A SYSTEM

Circuit Models for Teaching and Learning - a Didactical Problem

The electric circuit is often introduced in textbooks as a system in which energy is transferred from a voltage source to a consumer or resistor. This transfer of energy is accomplished by the movement of charged particles, the electrons, which are presumed to drift along inside a closed conducting (metallic) circuit. Since these drifting electrons cannot be observed directly, analogies or models are essential for understanding (Glynn, 1995). The question is: just what analogies or models are suitable?

An example of a very poor analogy is found in an American textbook, in which illustrations like that show in figure 1 are used (ISSC,1970):

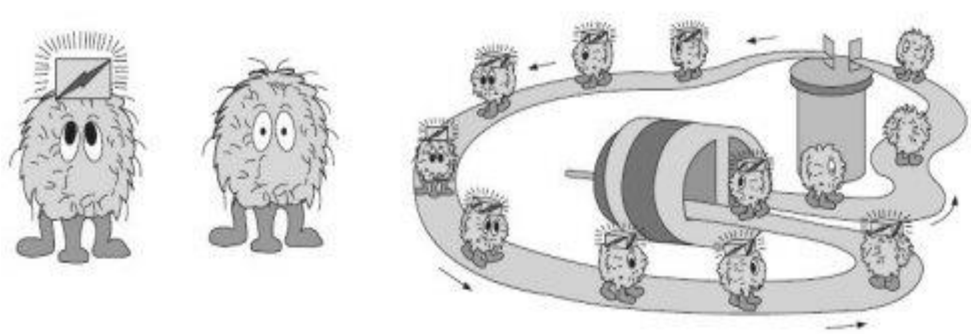

Figure 1. *A misleading Model for The Electric Circuit*
(Electrons with their own driving force (which does not exist of course)
are carrying energy from the battery to the motor and return without energy)

In this model the electrons are allocated their own drive, (which of course does not exist in reality). At the negative pole they are apparently charged with a package of energy, which they then carry in an orderly sequence to the motor before returning empty (and exhausted) to the battery.

One of the basic errors in this model of the electric circuit is that the drive for the circular motion is allocated to the individual particles. Thus, the system is apparently one in which the drifting velocity of the particles decides how rapidly the effect of the electric current is propagated through the system. But this model is unable to explain how an electric current propagates with the speed of light, even though the electrons are drifting rather slowly (and indeed, in case of alternating current, hardly even change location).

Similar discrepancies can be found. How can one explain that in respect to energy there is no difference between the forward and backward line? After the battery is switched off why is there no energy left on the forward line? Why do all the particles stop moving as soon as the circuit is broken at some arbitrary place? How do the particles in a circuit with more than one resistor "know" which part of the energy package they have to unload at the different serial resistors?

Relatively recent German textbooks use an analogy of skiers on a ski trail or trucks on a highway for the flow of electrons in a conductor. Again, the driving force for the current is allocated to the individual particles; the criticisms above remain valid and scientifically rigorous answers to the questions listed above are missing.

A slightly improved model for the movement of electrons might be a central heating system: The individual drive of the single particle is replaced by a central drive (a water pump) for the complete system. This allows one to explain how current can be switched on or off. When the pump stops or starts the current in the whole systems stops or starts. But again - and in contrast to reality - the propagation speed of the energy transfer remains coupled to the drifting velocity of the water and all related questions are left without reasonable answers.

Adequate Models for the Electric Circuit

Conducting electrons are indeed free to move, but unlike self-propelled particles they possess no individual mechanism of moving. The transfer of energy does not occur in the form of energy enriched matter, as in a central heating system, in a blood circuit or a conveyor belt but through forces, applied on the conducting electrons by the voltage source (repulsion at the negative pole and attraction at the positive pole). The conduction electrons transmit these forces to the existing resistors in the circuit. Together with the drifting electrons electric work is performed inside these resistors and therefore energy is transferred. The German word "Kraftwerk" (literally "force plant") for a power plant reflects the fact that in such a plant primarily a force is produced to set electrons in motion; this in turn can be converted to power as energy per unit time.

The conduction electrons can transmit these forces because they form a "stiff" ring (stiff in the axial direction). This "stiffness" can be explained by their mutual repulsion as well as via interactions with the positive lattice ions of the corresponding conductor. This interaction implies that strict neutrality exists within any metal conductor and that at no point there is any surplus or a shortage of electrons. If conduction electrons are drifting, they can only drift together so that neutrality is guaranteed at all points inside the conductor.

A bicycle chain or a water circuit - the latter, however, under high pressure and with rather small drift velocity - are more suitable models for the electric circuit, because here both force and motion are transferred and not energy enriched matter.

In the classroom this fact should be discussed in detail. It should be repeatedly discussed as a foundation for the interpretation of experiments and this in explicit contrast to the incorrect but quite common models listed above. This is an intellectually demanding task that cannot be mastered without effort and adequate opportunity for practice. If this effort is successful the chances are good that a deeper understanding of the topic can be achieved.

If, however, the electric circuit is treated only as an abstract system for the transmission of energy and if only the processes of energy transformation are discussed, a causal foundation for all the underlying processes is missing. For example, it is not clear how energy might be transferred both in the direction of the flowing electrons and in the reverse direction. Furthermore, the questions raised in connection with the misleading model shown in figure 1 cannot be answered conclusively. Finally, there is a risk that the view that energy transport can be equated to transport of energy enriched matter. This could result in the idea that energy consumption is equivalent to current consumption, a well-known rather robust misconception among students

The law of conservation of energy is unsurpassed in its generality but also in its abstraction, it is of limited use in teaching. The introduction of such a law in the classroom is often a description, not an explanation, and this can mislead students to conclude that explanations and laws in physics must be accepted but cannot be deeply understood. Such teaching may undermine the learner's motivation and interest.

INSTRUCTION FOR TEACHING

Transmission Of Energy Enriched Matter Versus Transfer of Force

When the electric circuit is first introduced at elementary or lower secondary level, the conditions for a current to flow (closed circuit) are discussed, the different components and symbols are assigned, and the difference between conductors and insulators is demonstrated.

To present this topic on the next higher level a curriculum may be helpful which was developed at IPN (Härtel, 1981). Although in its original form this material is no longer available, it has recently been recast in a revised and shorter net version (Härtel, 2010).

This curriculum comprises four sections which cover the topics:

- current and resistance in serial and parallel circuits
- electric voltage
- Ohm´s law
- application of circuit rules

with detailed instructions for classroom activities and teaching.

Although this material is written in German, the numerous figures should be helpful even to non-German speakers. The conception of this teaching unit is based on the finding that there is a significant difference between everyday ideas about power/current consumption and what actually happens inside an electric circuit (Härtel, 1982):

- The everyday view of power/current consumption is that energy is transferred as a sort of matter or as a property of transported matter. From this starting point, the transport of energy (or energy enriched matter) can be followed from the source through the conductors to the resistors without any reflection required about the system context. The rules and facts to be learned (i.e., that there is no current consumption) cannot be derived but have to be accepted.
- Energy transfer in a real electric circuit is completely different. An important feature of the circuit is some kind of force connection between the energy source and the consumer, while the energy is transmitted by forcing the movement of an interrelating ring of electrons around the circuit. This ring of electrons is stiff in axial direction were pulling and pushing forces can be applied. Some kind of system thinking is necessary where the complete system and its force connection must be kept in active memory. When this is possible all further rules and laws follow by derivation without any additional assumptions.

The Unbranched Circuit

In the light of these objectives, it is proposed that one starts teaching electric circuits with an extensive discussion about systems for the transmission of energy but limiting the initial discussion to the unbranched circuit (fig.2). During this discussion the special property of the bicycle chain should be emphasized in comparison with other circular systems, in which energy enriched matter is transmitted.

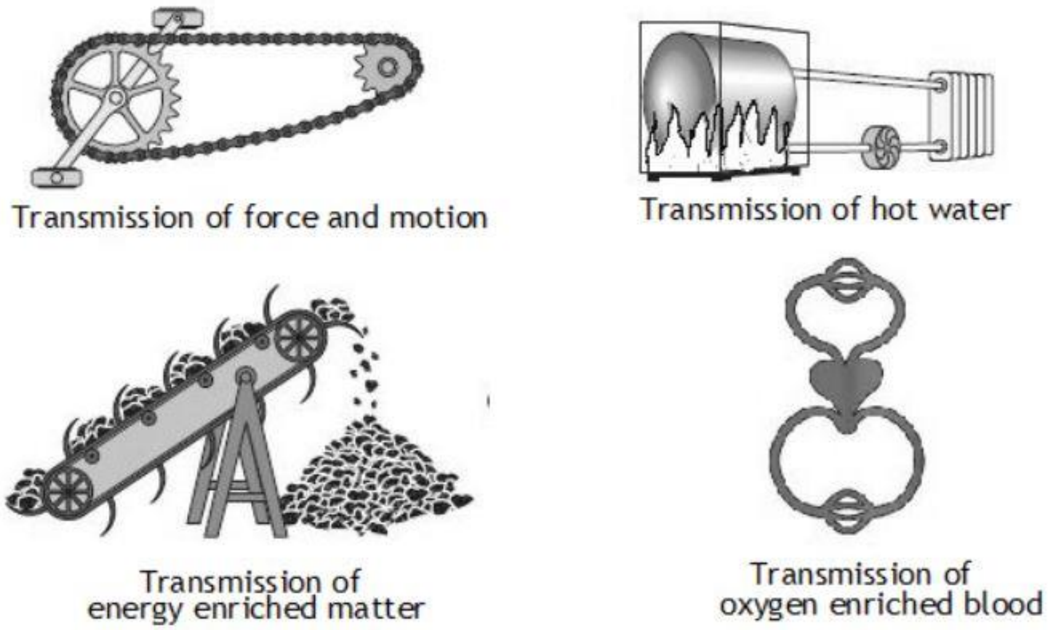

Figure 2. *Different Systems for Transmission of Energy*

All students are familiar with bicycle chains, so this is a helpful model of the electric circuit to accentuate the important difference between the transmission of energy in form of force and motion on one side and in form of energy enriched matter on the other side.

A similar approach using a drive belt was proposed by (Muckenfuß, 1992). A bicycle chain, however, can only be pulled at on one side, so a clear difference appears between the part under tension and the relaxed part feeding back to the energy source. This illustrates a limitation of this model since a battery interacts in a symmetric manner with both connected wires. A stiff ring, on which one can pull and push, eliminates this deficiency of the bicycle chain and is better suited to leading students to an appropriate picture of the electric circuit.

When developing the IPN-teaching unit, an improved alternative was proposed in comparison to the model in figure 1, where most of all it should be emphasized that the "electro-particles" form an interrelated ring (stiff in flow direction) on which the battery can pull and push (figure 3).

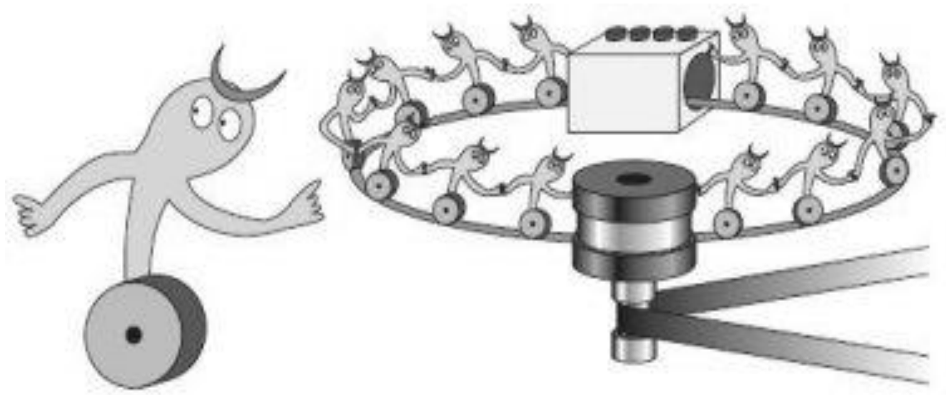

***Figure 3**. Improved Model for the Electrical Circuit, in Which the Connection Between the Particles and the External Drive is Clarified*

Our experience has shown that students find it difficult to identify and understand the important difference between these two models. In addition, the systems for the transmission of energy enriched matter support sequential thinking, which the students are familiar with and which they usually apply when considering electric circuits. With this approach the current flow is sequentially followed in a circle starting from the battery, and it seems almost necessary that different conditions must exist in front of and behind a resistor.

However, a system like the electric circuit, where energy is transmitted in the form of force and motion, is not well suited to a sequential analysis. Particularly in systems with multiple resistors, students are faced with higher cognitive demands because the entire system must be considered and the mutual interaction of all of its parts must be considered.

In order not to unwittingly encourage sequential thinking it is best not to describe the flow of electrons point-by-point around the circuit (figure 4 left), but to emphasize instead the simultaneous movement of all involved elements (figure 4 right).

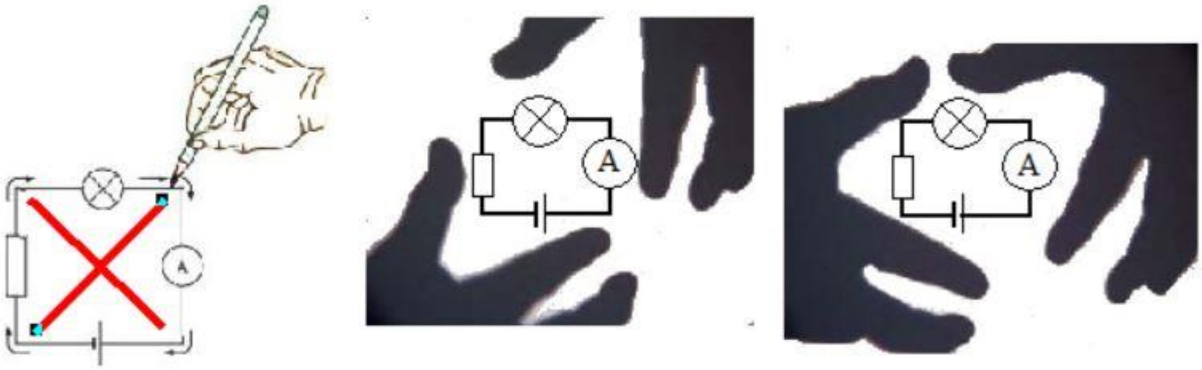

Figure 4. *Indicating the Movement of Electrons, not Point-By-Point From Minus to Plus (Left) But Collectively as an Interrelated Ring of Electrons*

In order to stimulate a deeper reflection about the difference between these two models, it can be helpful to organize some appropriate role playing (Sing, 2010).

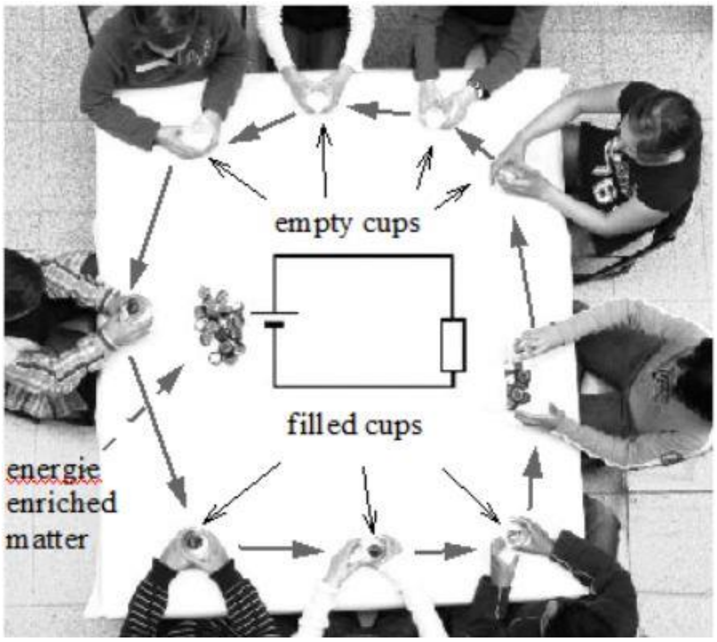

Figure 5. *Role Playing "Electric Circuit" (Inadequate Model: "Transmission of Energy Enriched Matter")*

In the first round each student passes a cup to his or her immediate neighbor. One student playing the role of the source fills each passing cup with "energy enriched matter" (coins, sweets). One student on the opposite side, who is chosen to play the consumer or resistor, empties each passing cup and performs some predetermined "work" (figure 5). A video, showing students playing this game, is found under: http://www.astrophysik.uni-kiel.de/~hhaertel/PUB/role-play.htm.

Different questions might be posed to test the validity of this model, for example:

- When the source has started to fill the cups, the energy enriched matter will move together with the cups, and it will take a while until the effect reaches the consumer. Is this in agreement with reality?
- When the consumer ceases emptying the cups, energy will remain on the feeding part of the circuit. Is this in agreement with reality?
- Only the feeding part of the circuit is carrying energy enriched matter, while the cups on the return part are always empty. Is this in agreement with reality?
- If one student inside the return path were to stop playing his or her role, all the other students inside the feeding part of the circuit could continue, at least for a while. Is this in agreement with reality?

In contrast to the transmission of energy enriched matter, a stiff ring (for instance a hula hoop) can be used to demonstrate, how work at some distant place can be performed by the transmission of force and motion. Such a ring can be supported by some students with a minimum of friction while one student is pushing and pulling and another at the opposite side is performing some "work" by applying some friction to the ring (figure 6).

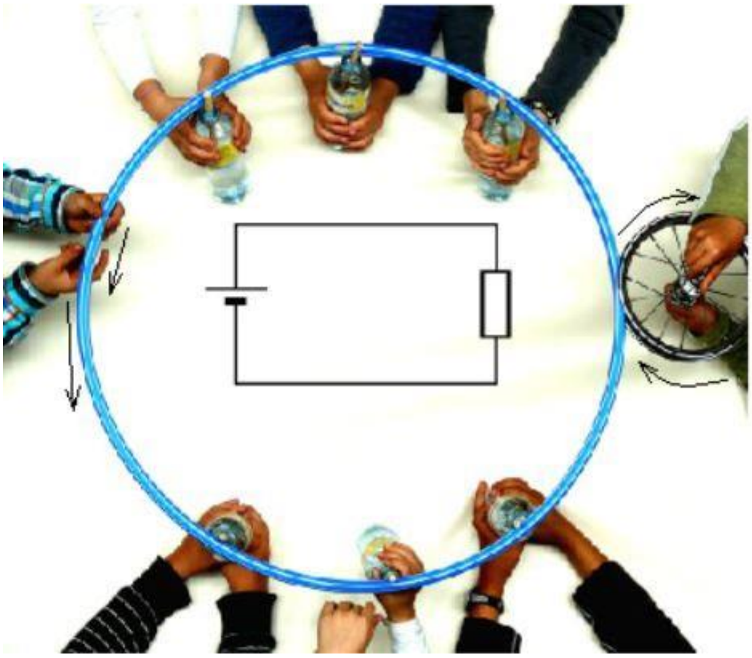

Figure 6. *Adequate Model: Transmission of Force Via a "Stiff Ring" by Push and Pull*

The same questions as before can be posed for this model; the answers will be far more in accord with the properties of a real electric circuit. As a result of this discussion the students should have learned and understood that an electric circuit can be described in abstract form by three terms:

- a drive, where energy is transferred to the system
- a flow of matter in the form of a closed circuit
- a hindrance (obstacle), where the energy is removed from the system.

It can be symbolized as follows (figure 7):

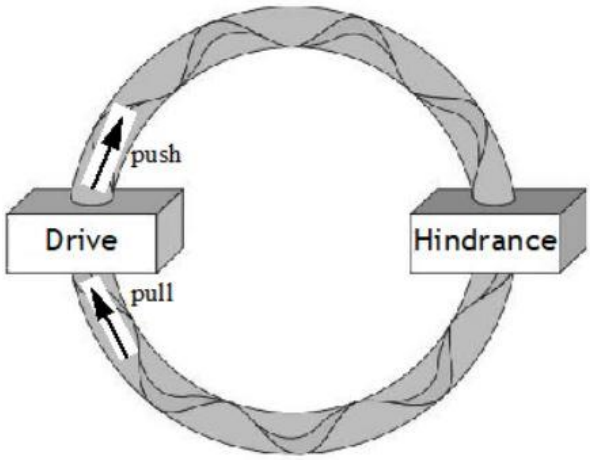

***Figure** 7. Symbol For an Electric Circuit (Without Branching Points)*

When using this symbolic representation for a circuit with a source for alternating voltage, the changing direction of the current can only be indicated with the help of appropriate arrows (figure 8).

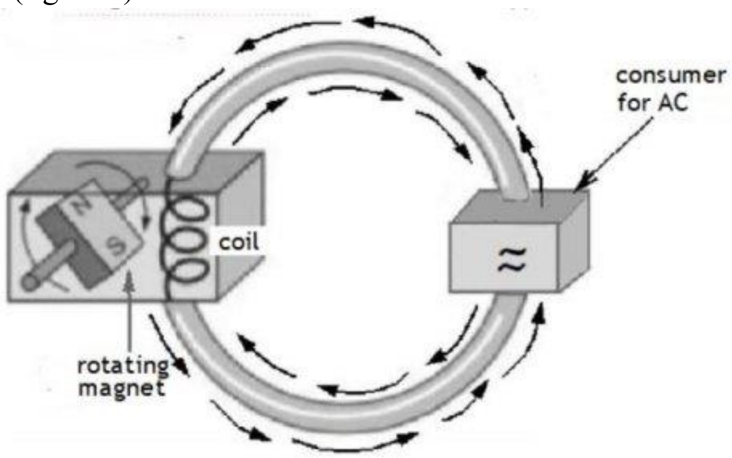

***Figure 8.** Symbolic Representation of an Alternating Voltage Powered Circuit*

(The Arrows Indicate the Changing Direction of The Current.)

If one postulates a transformer as a device that like a gearbox transforms a large movement with a small force into a small movement with a large force, then it is also possible to represent AC circuits with a transformer connection.

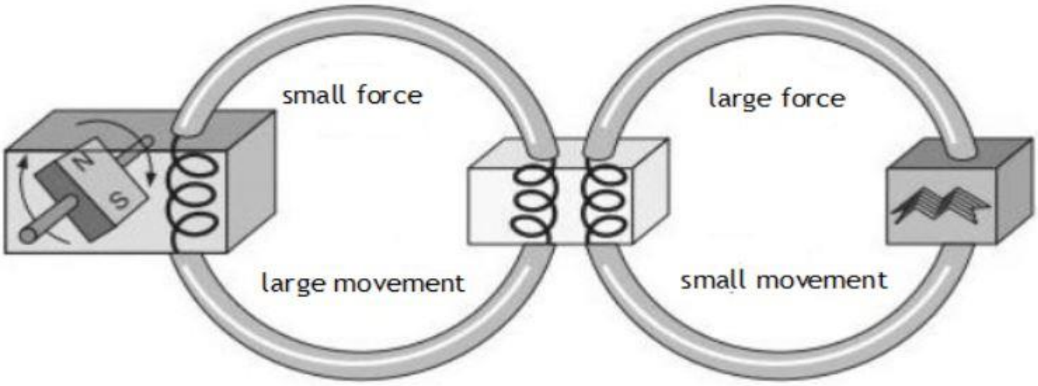

Figure 9. *Symbolic Representation of an AC-Current Connected to a Transformer*

Such a symbolic representation can also be applied to the case of an ac-circuit. Postulating a transformer as a tool which works analogously to a gear drive (transforming a large force and small motion to a small force and large motion and vice versa), a representation of an ac-circuit including a transformer will look like the following.

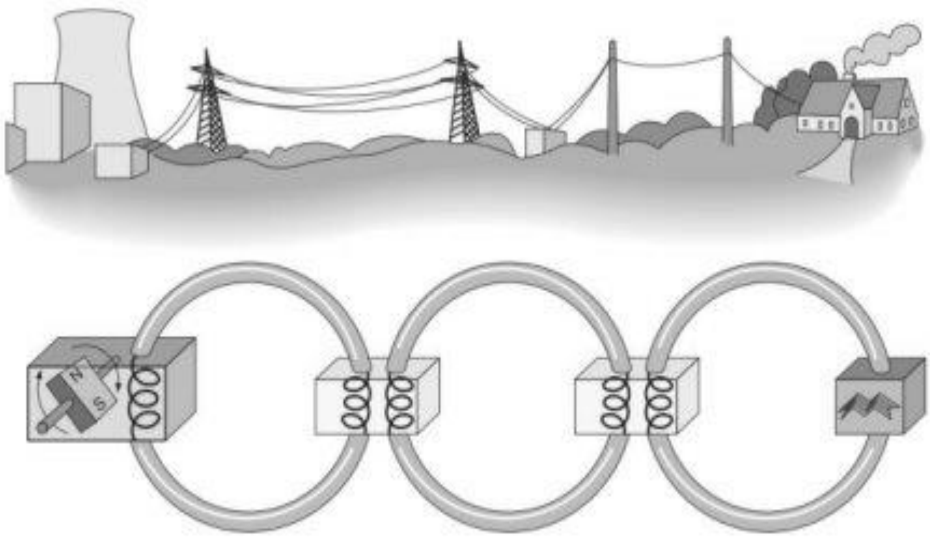

Figure 10. *Symbolic Representation of The Interrelation Between Power Plant and Private Houses*

The central idea is that at each moment all parts of the system are interrelated by some kind of tension, caused by the drive on one side and the hindrance on the other. Finally, this picture could be related to the power distribution over large distances, where losses on the lines are reduced by transforming the voltage twice, first to high and later to lower values - and the opposite for the current.

The central idea is once again that all these different circuits form an interrelated system were pulling and pushing forces are applied by the source on one side and the consumers on the other.

The Branched Circuit

The models presented so far (bicycle chain and stiff ring) are no longer adequate if circuits with parallel branches are included. For this purpose, a closed system filled with a liquid can be used as a model for the electric circuit under the assumption that the following conditions are fulfilled:

1. Within the closed system only laminar flow occurs; no turbulence exists.
2. The kinetic energy of the flowing liquid is insignificant; this requires that the drift velocity is rather small.
3. Since the drift velocity is small, a rather high-pressure difference between different parts of the system is needed to achieve a reasonable rate of transmission of energy.

Quite a few examples for water models can be found in literature and textbooks (see for example (Pfister, 2004) to be used as analogy to the flow of free electrons within a circuit. As (Bude and Wilhelm, 2020) have shown, also the pressure difference in an air-filled system can be used mainly as an analogy for potential difference.

In comparison with the electric circuit, however, all these technically realized water models suffer in one important aspect: the ratio between the kinetic energy of the flowing water and the size of the driving forces. In the electric case this ratio is huge. The kinetic energy of the free electrons is practically zero, the driving force - the EMF - is dominant. Water in a closed system, however, when continuously driven by a pump, inevitably gains kinetic energy and the existing pressure differences are less dominant. Such models therefore risk to stimulate ideas like those discussed along figure 1.

It is quite difficult to realize a closed water circuit under high pressure and small drift velocity. During the development and evaluation of the IPN-teaching unit a so-called “syringe model” was introduced (figure 11).

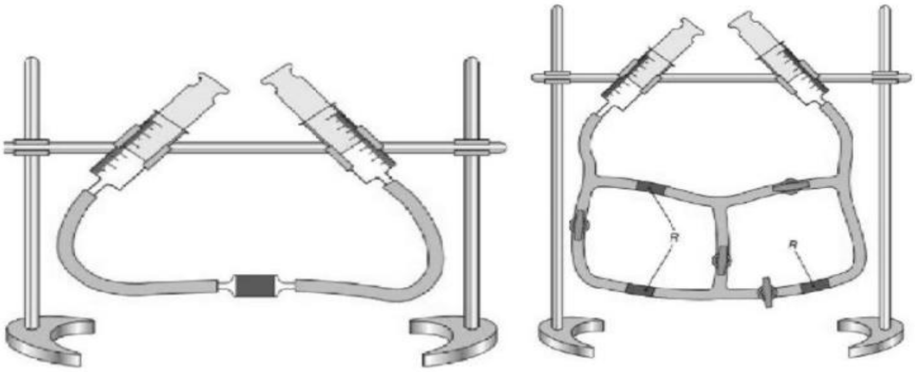

Figure 11. *Syringe Model as A Substitute for A Closed Circuit*

(A video showing this syringe model in action is found under:

http://www.astrophysik.uni-kiel.de/~hhaertel/PUB/syringe_model.flv

For more details about this syringe model please contact the author)

Thinking of the two syringes as continuous, we obtain a quasi-closed system analogous to the electrical circuit where a stationary current can flow for a short period of time. Such a model has the advantage that students can apply their own force to the syringes and experience directly the difference in resistance between parallel and serial resistors. Additionally, this difference can be improved by rearranging the model and measuring the period of time and the displaced volume for a given weight (figure 12).

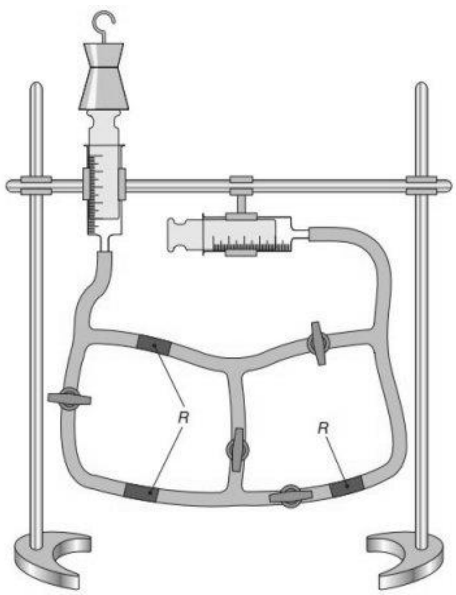

Figure 12. *Rearranged Syringe Model to Measure the Current*

Experience during different evaluation phases has shown that the introduction of a water current can be helpful for students because it is a concrete object which provides analogies to the abstract flow of electrons inside an electric circuit.

Early studies, however, have shown the limits of this support (Schwedes, 1995). It is by no means trivial to fully comprehend the conditions within a closed water circuit with serial and parallel resistors just because it is a concrete object. A full understanding requires an appreciation of the meaning of pressure within a water current and here students normally fail. To reduce this difficulty the following figure 13 of a real experiment can be used, where a bicycle tube has been connected to a tap and the water is pushed through a bottleneck.

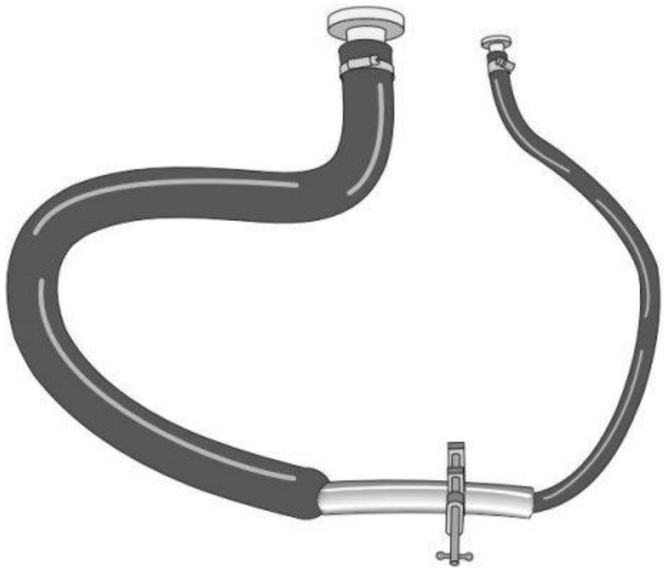

Figure 13. *Water Current through an Elastic Tube with a Bottleneck*

The elastic tube directly indicates the local water pressure. It can be clearly seen that there is no congestion in front of the bottleneck, as often assumed by students.

In a similar experiment it can be demonstrated that contrary to the usual belief, the pressure is not reduced behind a branching point but remains the same (figure 14).

Figure 14. *Water Current Through an Elastic Tube with Two Parallel Bottlenecks*

It is more demanding to explain the distribution of pressure within a laminar flow than it is to just measure it. Firstly, students must accept that water is indeed compressible, contrary to the widely held view that it is incompressible. To correct this misconception, it may be helpful to learn that the surface of the oceans would rise by about 40 m, would water be incompressible and would not be compressed by its own weight.

A laminar flow through a bottleneck or resistor can only occur if there is a pressure difference across this resistor. This arises because the water is compressed to a different extent before and after the resistor and reacts according to elastic counter forces. It follows that the water leaving the resistor has a slightly lower density and a slightly higher drift velocity than entering the resistor.

The fact that this difference is rather small does not mean that it can be neglected. Indeed, the difference is vital because there is no other way to explain the stable pressure difference within a laminar flow.

Once these facts are understood it becomes clear why there is no bottleneck effect in a water circuit with serial resistor. A bottleneck effect exists, for instance, in the flow of road traffic where the main obstruction is the sole factor that determines the total number of cars passing per unit time; all less serious obstructions can be neglected. In a closed water circuit, however, all resistors add to the total flow rate because a pressure difference is necessary for each resistor to keep up a constant flow.

An equivalent argument holds for the fact that we find the same pressure difference across parallel resistors even though they have different values.

Students normally are not aware of the relation between pressure and compressibility of water. If pressure is introduced through its measurement with a manometer or a vertical water column, a new term must be learned whose behaviour in more complex arrangements cannot be predicted but must be accepted for each new case. The support for learning and understanding by introducing the water model will therefore be limited unless the above more complex interrelations are explicitly treated.

The difficulty which students have when dealing with pressure in a laminar flow becomes evident when they are asked to draw the flow of water through an elastic tube with a bottleneck. Many students produce a drawing like that shown below or accept such a drawing as correct (figure 15).

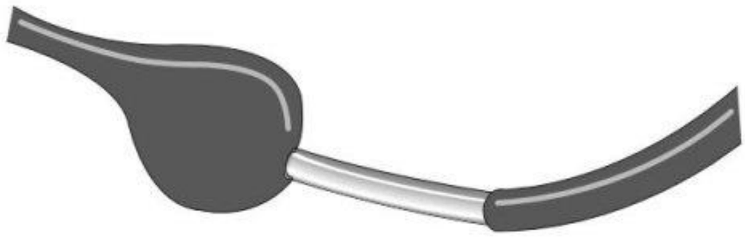

Figure 15. *A Frequently Encountered Student Drawing (About the Distribution of Pressure Before and Behind a Bottleneck)*

This drawing is not completely wrong if we consider just the initial processes. After the flow has been switched on, a momentary congestion will appear in front of the bottleneck, causing a reflection and leading finally to a stationary state with a constant pressure in both parts of the tube. Such a drawing should therefore not be immediately rejected but could be used as a fruitful starting point for a discussion about the relation between stationary states and transition processes.

A grasp of the relation between pressure and compressibility is helpful in understanding not only the water model but also the relation between voltage and surface charges. Here again a better comprehension of the term voltage can be reached if the conduction electrons are seen as some kind of "electron gas" with a certain compressibility. When applying a voltage this "gas" reacts by placing extra charges on the surface of the conductors which then oppose any further compression.

In a following article, this relation will be described in detail, together with proposals for suitable classroom activities.

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