The so-called simple electric circuit -

it is not that simple

Abstract

The traditional treatment of the electric circuit in textbooks can be criticized in at least three respects:
1. Knowledge of the global aspects of the electric circuit as a system is essential for a deeper understanding. However, this is not sufficiently emphasized.
2. The introduction of the term “potential difference” or “voltage” as energy/charge is unnecessarily abstract because any connection to the surface charges, which always exist, is left out.
3. Treatment of the electric circuit, based on Ohm´s law and Kirchhoff´s rules, is exclusively based on stationary states, without any mention being made of the transition processes which must occur.

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.

1. 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 their own performance. This individual experience of success, bringing with it an enhanced belief in their own ability, may create a long lasting interest in climbing. If the task is too simple, the climbers may lose their initial desire and decide instead to pursue other kinds of sport.

There are parallels in the physics classroom. Alpine climbing is regarded by non-climbers 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 what is required of the physics student is mere rote learning 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.

Learning research over the last 30 years tells us that most of our students do not fully understand even some of the basic features of the so-called simple electric circuit (in our mountaineering analogy, they do not reach the summit). Students with high grades in physics exams, when confronted with slightly modified problems, often approach the revised problem weighed down by the same misconceptions they held before, rather than making use of the principles presented in the classroom, [1] [2].

Much effort has been invested over the years in the study of these misconceptions [3] [4] . Unfortunately, not much success can be reported in fostering any long lasting conceptual change among students that might lead them towards a scientifically acceptable perspective.

Most students fail to reach the learning goals set by their teacher; for example, the well-known misconception about current consumption is rather robust and persistent [5] [6].

We argue here that one key reason for this failure is the somewhat uniform way in which academic content appears in most traditional textbooks. The degree of difficulty is frequently misjudged, being sometimes too low and sometimes too high; this error is then compounded by the presentation of material in a manner that is often essentially incomplete.

Let us illustrate this, with particular reference to electric circuits. We would argue that the degree of difficulty is too low if the content is presented without an explicit and intensive treatment of the global aspect of the circuit as a system.

By contrast, the degree of difficulty is too high if the fundamental term voltage is defined and explained only as energy per unit charge without referring to surface charges.

And the presentation of content is incomplete if only stationary states of the electric circuit are treated (where Ohm´s law and Kirchhoff´s rules are valid) without including the inevitable transition processes which are necessary for a deeper understanding of the electric circuit.

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”.

2. The Electric Circuit as a System

2.1. Circuit Models for Teaching and Learning - a Didactical Problem

The electric circuit is usually 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 student understanding. 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 shown in figure 1 are used [7].

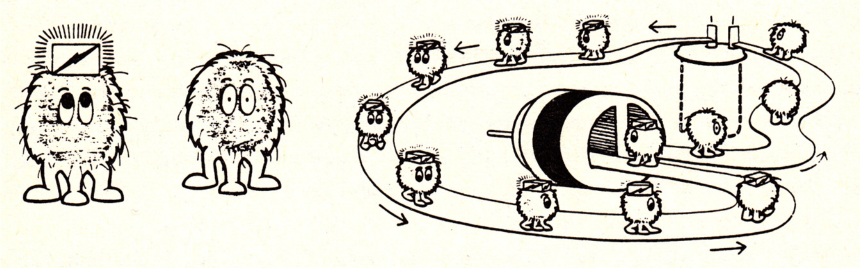

Fig. 1. A misleading model for the electric circuit
Electrons with their own driving force (which in reality does not exist of course)
are carrying energy from the battery to the motor and return without energy

In this model the electrons are allocated their own drive, (which in reality does not exist of course). 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 electrical 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 the case of alternating current, hardly even change location).

Similar difficulties abound. 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 the electrons might be a central heating system: the individual drive of the single particle is replaced by a central drive of the system (a water pump). 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.

2.2. Adequate Models for the Electric Circuit

Conducting electrons are indeed free to move, but unlike self-propelled particles they possess no individual motor. 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 force is produced to set electrons in motion; this in turn can be converted to power as energy per unit of time.

The conduction electrons can transmit these forces because they form a “stiff” ring (stiff in the axial direction). This “stiffness” arises from 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 is there 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. The word “inside” is important, because there is an exception as we will see shortly.

A bicycle chain or a water circuit - the latter, however, under high pressure and with rather small drift velocity - are 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 taken 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, but 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, and that energy consumption is equivalent to current consumption, are not considered sufficiently critically, and therefore may endure beyond the lessons.

The law of conservation of energy is unsurpassed in its generality, but also in its abstraction, so is of limited use in teaching. The introduction of such a law in the classroom is often a description, not an explanation, and this brings the danger that students may 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.

3. Instructions for teaching

3.1. Consumption of current 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 in 1981. Although in its original form this material is no longer available, it has recently been recast in a revised and shorter net version [8] [9].

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.

- 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 closure 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. The term force closure is used for a stiff connection (stiff in axial direction), where pulling and pushing forces can be applied.

  Some kind of system thinking is necessary where the complete system and its force closure must be kept in active memory. When this is possible all further rules and laws follow by derivation without any additional assumptions.

3.2. 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 initial discussion to the unbranched circuit. During this discussion the special property of the bicycle chain in comparison with other circular systems, in which energy enriched matter is transmitted, should be emphasized.

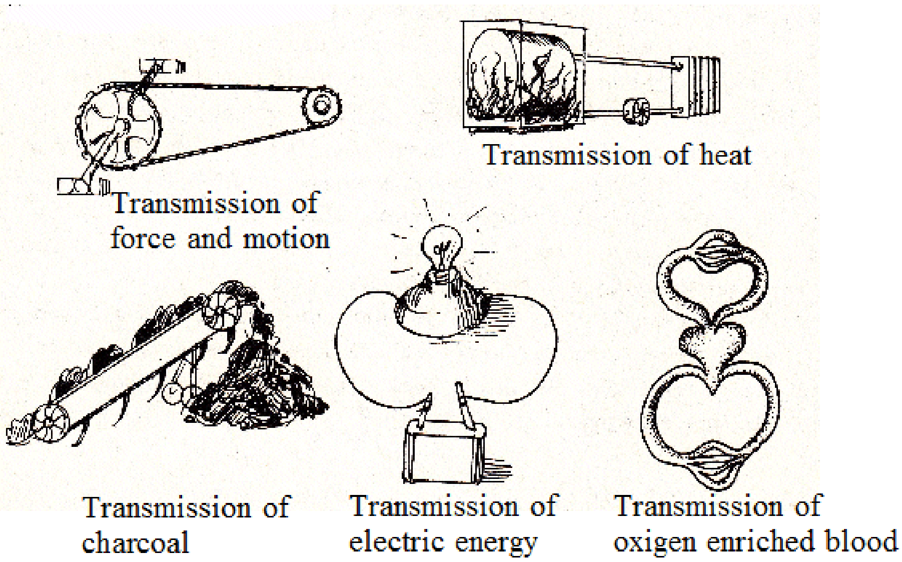

Fig. 2. Different systems for transmission of energy

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

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 even 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 on which the battery can pull and push (figure 3).

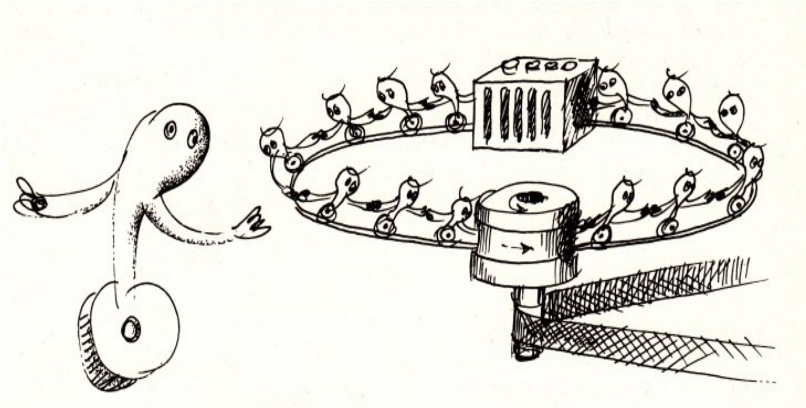

Fig. 3. Improved model of the electric circuit,
where the interrelation between the particles and the external drive is emphasized

Our experience has shown that students find it difficult to identify and understand the decisive difference between these two models. One reason for this difficulty may be that a system in which matter is transmitted can be analyzed sequentially; it is this type of thinking which is most familiar to students and which they usually apply when studying the electric circuit. They look at the current which leaves the source and moves around through the circuit while passing one by one through different resistors. On the basis of this kind of thinking it seems quite natural, if not absolutely necessary, that the conditions before and after a resistor should be different (if no current is consumed, then at least energy).

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

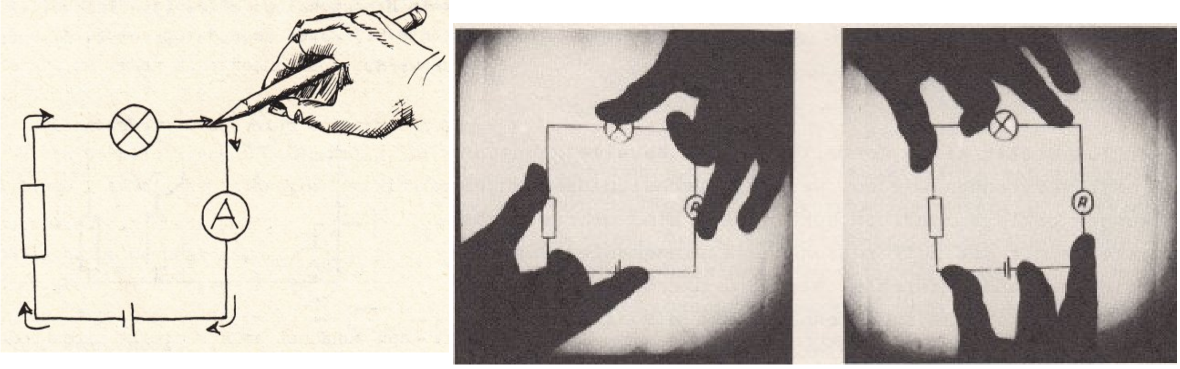

Fig. 4. Indicating the movement of electrons,
not point-by-point from minus to plus (left) but collectively as an interrelated ring of electrons

In order to stimulate a deeper reflection about the difference between these two models, it can be helpful to organise some appropriate role playing [10] [11].

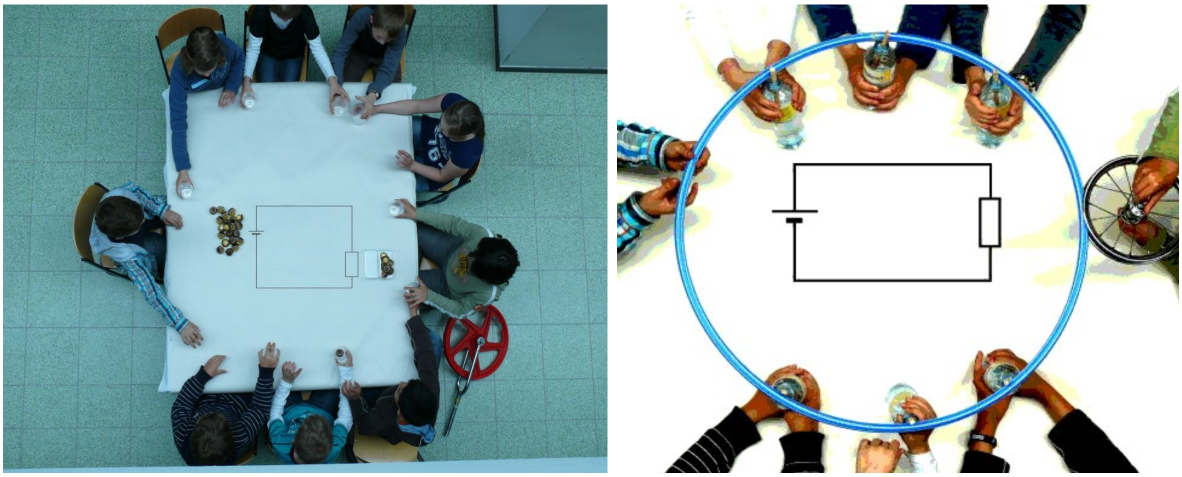

Fig. 5. Role playing "Electric circuit"
(left: Inadequate model "energy enriched matter"; right: adequate model "stiff ring")

In the first round each student passes a cup to his or her immediate neighbour. One student who takes 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).

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 in 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” (figure 5 right).

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,

and can be symbolized as follows:

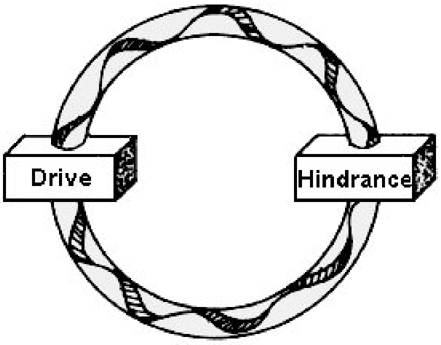

Fig. 6. Symbol for an electric circuit (without branching points)

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:

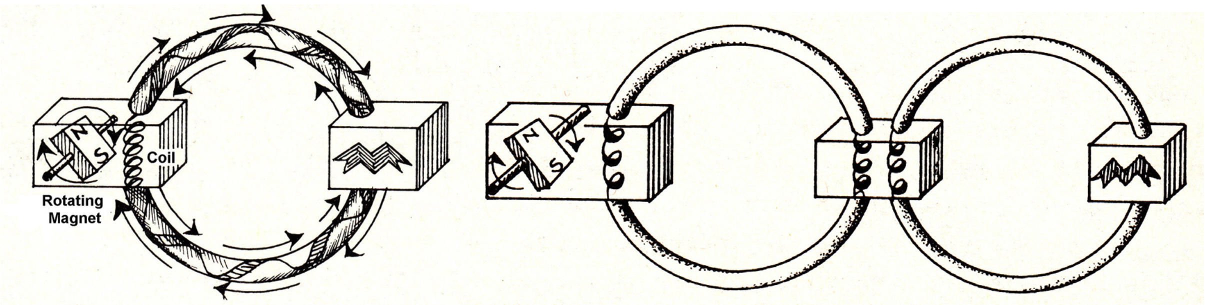

Fig. 7. Symbolic representation of ac-current with and without connection to a transformer

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 nationwide system of electric energy supply, where losses on the lines are reduced by transforming the values for voltage twice, first to high and later to lower values - and the opposite for the current.

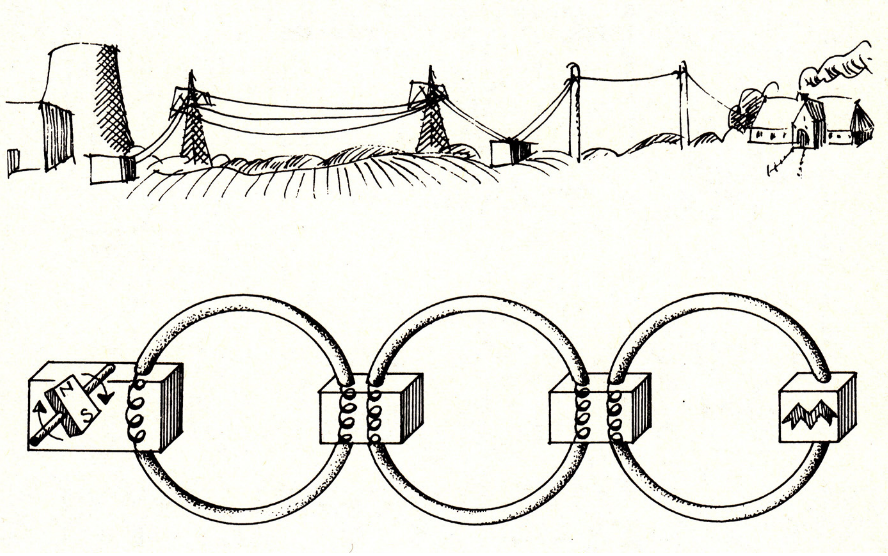

Fig. 8. Symbolic representation of the interrelation between power plant and private houses

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

3.3. 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 the literature and textbooks (see for example [12]) to be used as analogy to the flow of free electrons within a circuit. 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 absolutely 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 9).

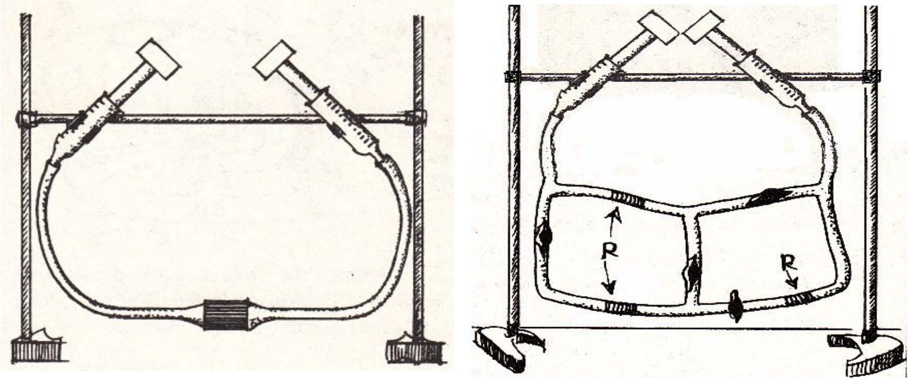

Fig. 9. Syringe model as a substitute for a closed circuit

If one thinks 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 10) [13].

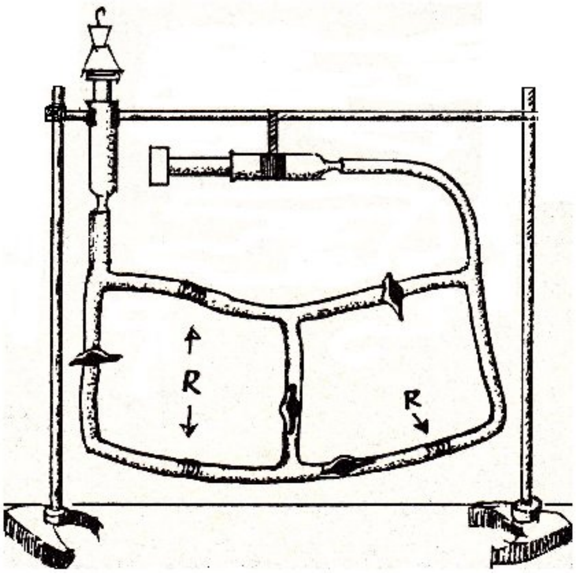

Fig. 10. Rearranged syringe model to measure the current
(weight, displaced volume, period of time)

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 [14]. 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 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.

Fig. 11. Water current through an elastic tube with a bottleneck

The elastic tube indicates directly the local water pressure; it can be clearly seen that there is no congestion in front of the bottleneck, as is 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.

Fig. 12. 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. First, 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, were water incompressible and not 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 when it enters 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.

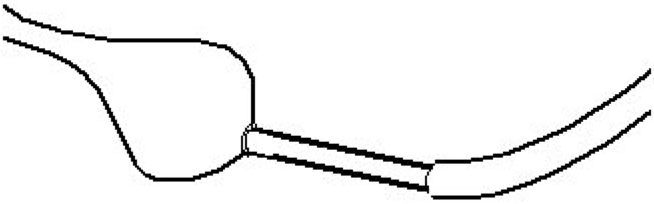

Fig. 13. A frequently encountered student drawing
(about the distribution of pressure before and behind a bottleneck)

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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To have students in the role of charge carriers, however, is problematic, since the most important fact of an interrelated system is missing.

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