

Nature does not make leaps - and this holds also for OHM's law

This article was originally published in the German Journal
„Praxis der Naturwissenschaften-Physik“ (PdN-PhiS_2012_5_S_31-36)

Translation: Hermann Härtel
(Figures improved by PdN - PhiS)

Abstract

Ohm's law and Kirchhoff's laws are based on stationary states. These laws do not provide evidence of the ever-present transition processes that connect these states and bring about their particular setting. However, by using suitable simulation programs, transition processes become accessible classroom activities, allowing a deeper and more coherent understanding of the processes involved.

1. Stationary states without transition - a teaching problem

The topic "Electrical circuits" is a part of physics teaching in virtually every country, but in this teaching it is common practice to treat only stationary states, ignoring the ever-present transition processes.

In a test in different European countries students were asked the following question:

- Consider an electric circuit, consisting of a battery and a resistor, in which the current flow- ing is given by Ohm's law (figure 1).



Fig. 1. A simple electric circuit with variable resistor.

If the resistance is abruptly altered, the current changes such that a new steady state is reached, which is again described by Ohm's law.

Question: How does the transition process from one steady state to another take place?

The result of the test was clearly negative [1]; most students had never heard of transition processes.

Transients in electrical circuits are usually very short-lived and difficult to determine experimentally, which may be why they are omitted from the teaching process.

If the aim of physics teaching is to foster accurate observation and precise thinking, this traditional approach is problematic. Students should not learn only about steady states; they should also consider questions such as:

- How does the battery "know" that the resistor at some distance from it has been changed, and that the current must be adjusted?

or

- How rapidly does the current increase, if a short circuit occurs in the circuit?

Do our students learn, that fast processes are not important? Do they learn that you may accept action at a distance to answer such questions? In case students do not pose such questions: Should not they be sensibilized to recognize that the causal explanations for the electrical circuit

are fragmentary without the inclusion of transition processes?
Modern simulation programs provide a way to meet this need, as shown below.

2. Instructions for teaching

2.1. Experimental demonstrations

The demonstration of a transition process in a circuit with a large capacitor is straightforward.

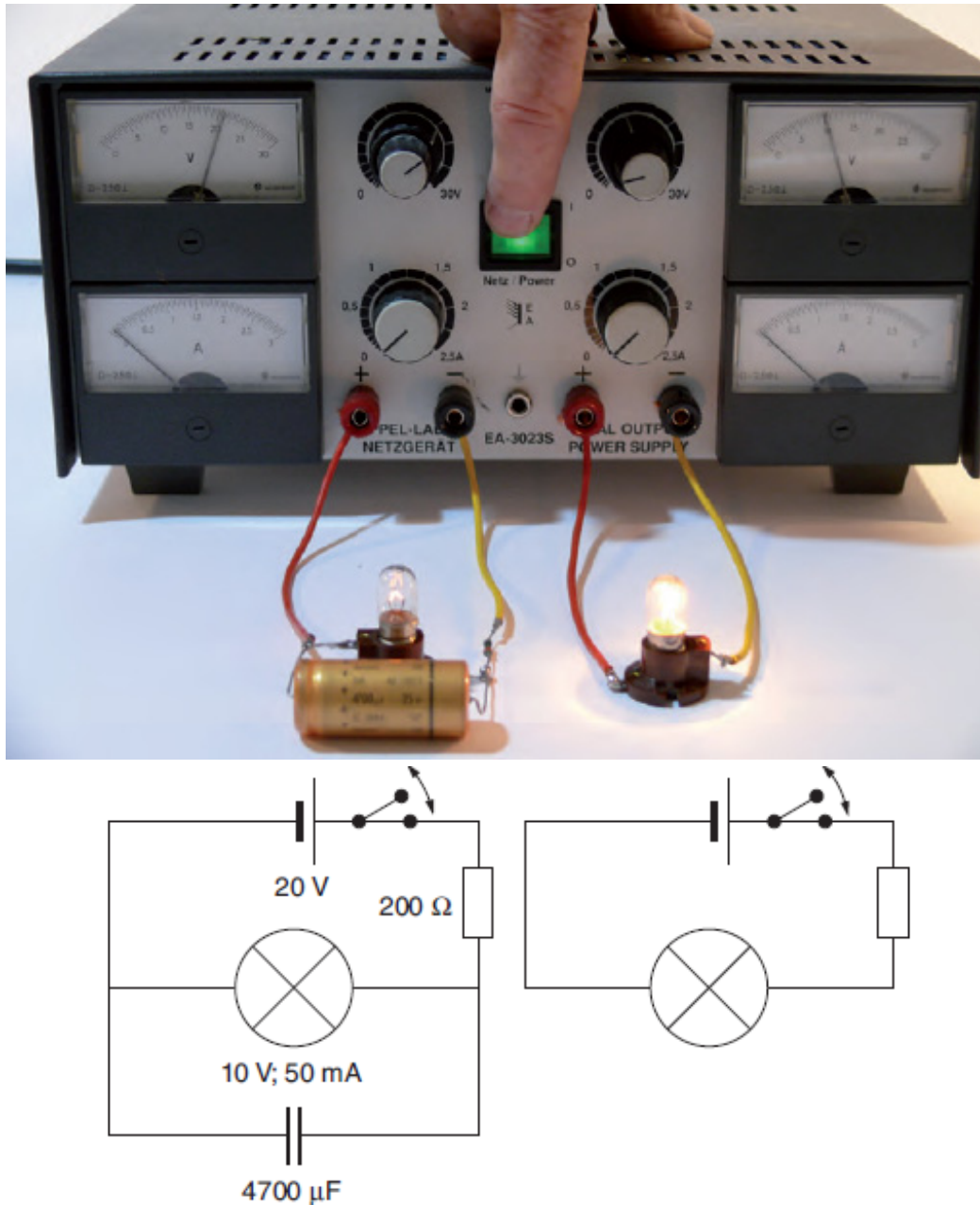


Fig. 2. Demonstration of a transition process.

If the bulbs are not directly connected to the voltage source (fig. 2 right), but in parallel with a capacitor (left), then the delay caused by the charging and discharging of the capacitor becomes clearly visible [2].

To interpret this experiment, the student needs to understand the behaviour of capacitors. This in turn requires a knowledge of surface charges and a knowledge about the fact that conductors in every circuit form capacitors which must be charged or recharged during each transition pro-

cess.

The experiment on the left in figure 2 therefore mimics the experiment on the right. The conducting elements that connect the source and the lamp have to be charged and de-charged whenever the lamp is switched on and off and this will cause a delay, albeit a rather brief one. The capacitor connected in parallel just increases the surface of the conducting elements to make the transition process apparent.

2.2. Use of simulation programs

2.2.1. The program CLOC - Conceptual Learning Of Circuits

For the explicit treatment of transitional processes in the classroom, a simulation program called CLOC (Conceptual Learning Of Circuits) may be helpful.

This program was originally developed to support more broadly the treatment of the electrical circuit in the classroom [3] and is particularly relevant to the transition processes discussed here. The program allows one to build simple circuits with a voltage source, resistors, interactive switches and connecting elements (conducting wires). The strength of the current is displayed graphically and numerically. A three dimensional representation of the complete circuit is displayed in a separate window, showing the potential distribution over all elements. The program CLOC can be run as a standalone Java application or as an applet inside a WEB page. [4][5].

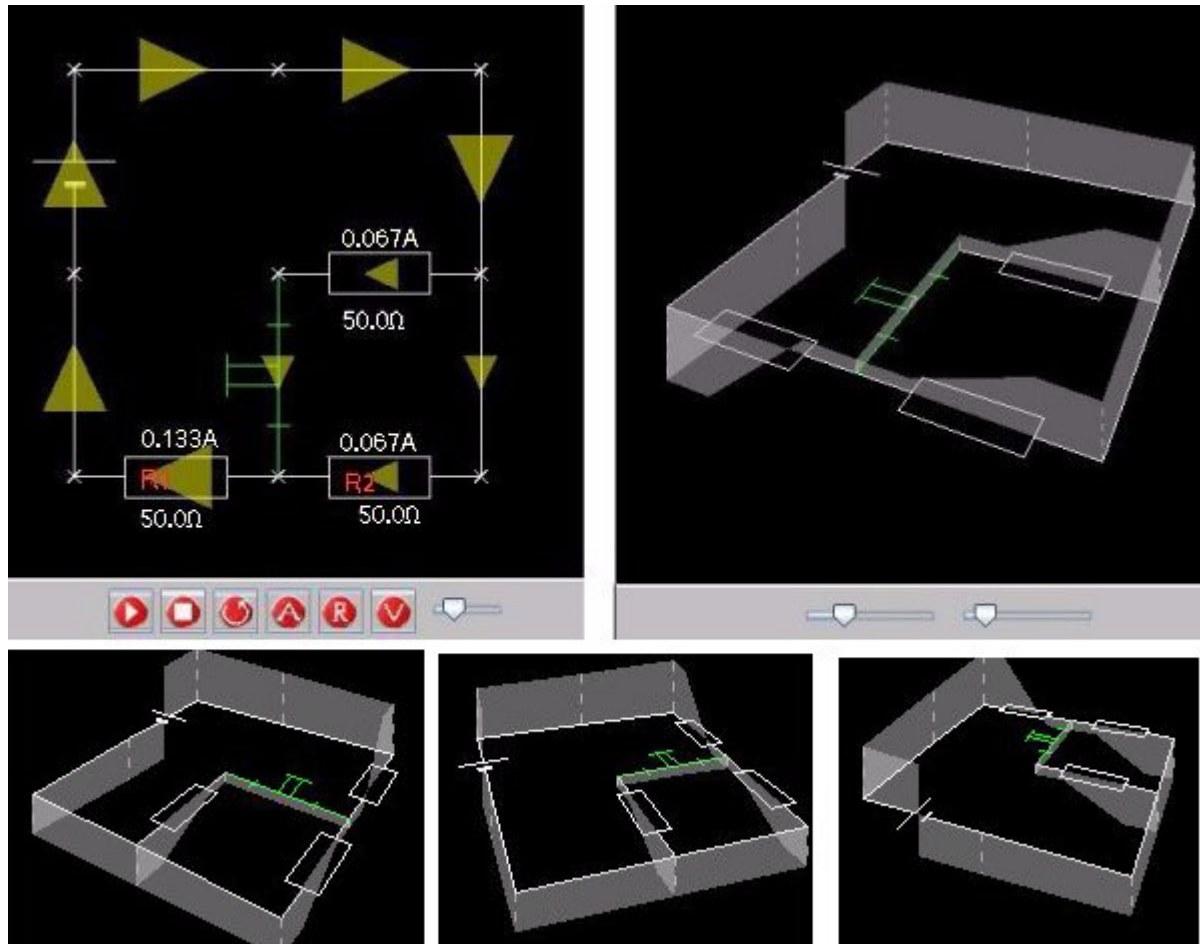


Fig. 3. Fig. 3. Screen displays of the simulation program CLOC (with variable perspective on the window with a 3D-representation).

This algorithm is based on the so-called container model. In this model, a resistor is treated as

such, while the adjacent circuit elements are modelled as containers.

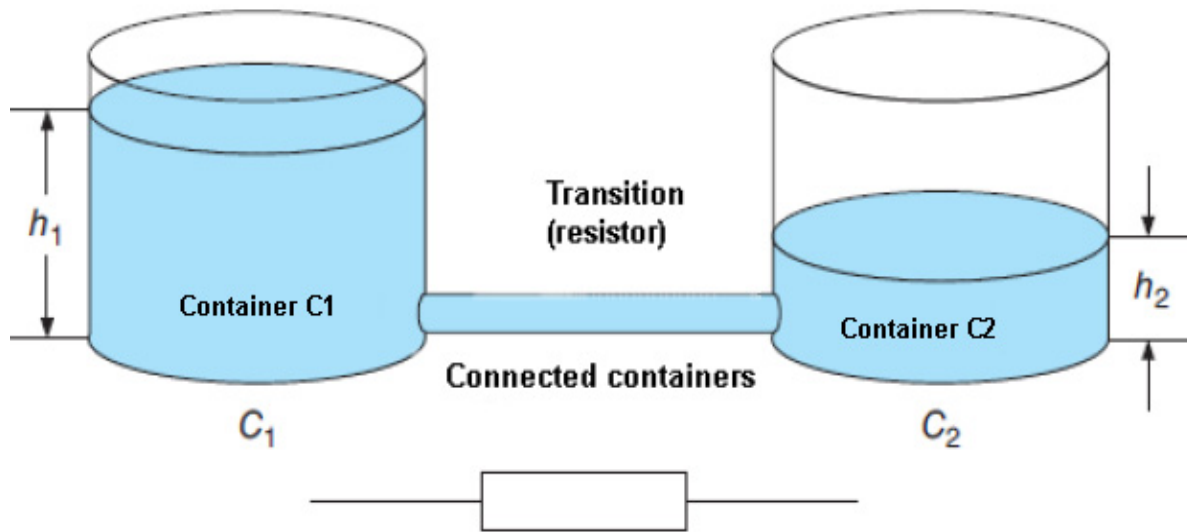


Fig. 4. Model for a resistor with two connections.

After using this procedure to decompose a circuit into single elements, the program determines continuously the difference in content of all adjacent containers ($h_1 - h_2$). A certain percentage of this difference in content (as determined by the connecting resistor) is then moved from one container to the next in order to reach an equal distribution (in the upper example from C1 to C2). An exception is the battery which maintains a predetermined difference in the contents of its adjacent containers.

After starting the simulation, the difference in content over the battery gradually spreads to all connected containers over a period of a few seconds, whereupon the system reaches a final stationary state. This final state is in every case consistent with experimental measurements.

The final state could be calculated directly using Kirchhoff's laws and this method is used in many simulation programs. From a teaching perspective this is not ideal however, because it relates only to steady states which seem to be reached instantaneously whenever a system change occurs.

The container model can be criticized on two grounds.

- Firstly, the delay shown is only roughly equivalent to the conditions in an electric circuit with large capacitors. Roughly means that the container model does not take account of reflections, which are especially dominant in circuits with small capacitors.
- Secondly, each contiguous conductor element is modelled as a single container and propagation processes are omitted along such circuit elements

These restrictions are acceptable, if one regards the transition processes in CLOC as approximations, and of value primarily as an educational tool to highlight the transients which would otherwise be ignored.

A second simulation program was developed, named "TL-Transition Line", where transients can be shown on a linear twin line. But this time all transients and steady states are exactly calculated and visualized. The highly exaggerated and simplified displays shown with the program CLOC can therefore be regarded as intermediate steps, followed by the use of TL to demonstrate real world behaviour.

2.2.2. The Simulation program "TL-Transition Line"

A visualization of transition processes on a twin line is offered by the simulation program "TL-

Transition Line" (figure 5).

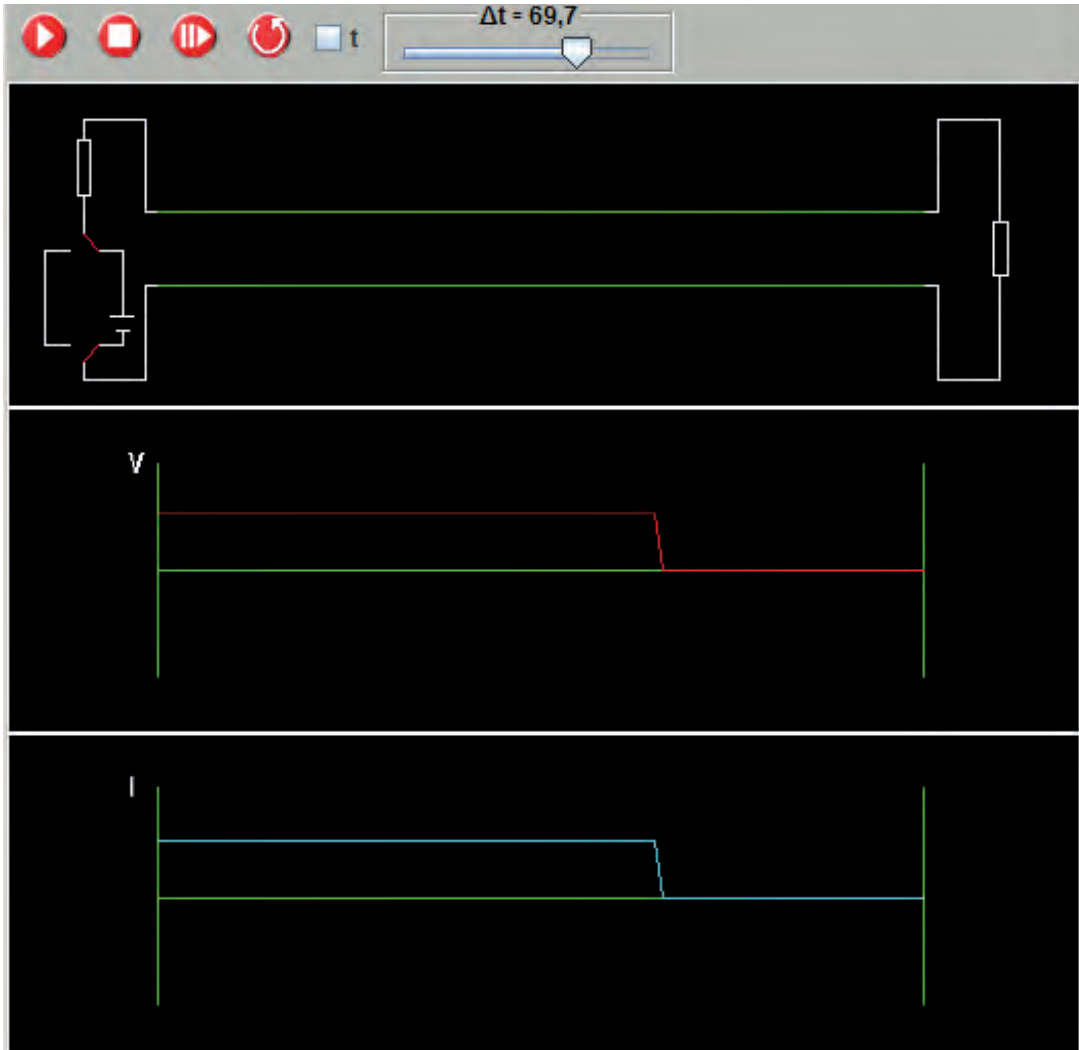


Fig. 5. Starting process of a dc-current on a twin line.

The implemented algorithm calculates a numerical solution of the following two differential equations, also known as "transport equations"

$$\frac{\partial}{\partial x} I(x, t) = -C \frac{\partial}{\partial t} V(x, t) - V(x, t)G \quad (1)$$

$$\frac{\partial}{\partial x} V(x, t) = -L \frac{\partial}{\partial t} I(x, t) - I(x, t)R \quad (2)$$

These equations can be derived from a configuration, where a twin line is modelled as a sequence of identical elements, as follows:

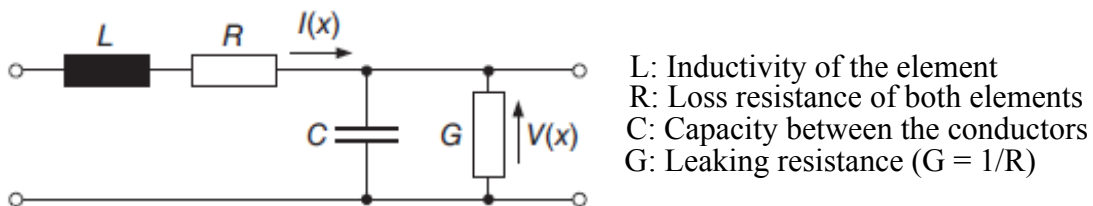


Fig. 6. Element of a twin line.

The twin line as displayed in TL consists of 200 such elements, although these are not shown

on the screen.

The equations above are derived by applying the knot rule (equation 1) and the mesh rule (equation 2) to each single element (with L , R , C , G per unit length). The same result is derived by solving Maxwell's equations in one dimension.

Numerical solution of these differential equations, together with the corresponding boundary and initial conditions, results in the functions $V(x,t)$ and $I(x,t)$, which are displayed in parallel to the twin line (figure 5).

The assumption for this one-dimensional solution is a long linear line where changes in the vertical direction can be neglected. The implemented algorithm has proven to be stable for all boundary and initial conditions without showing any unrealistic effects due to improper numerical methods. The program is written in Java and can be used as a standalone application or as an applet inside a WEB page [6].

Originally, this program was developed to support the teaching and understanding of wave propagation in linear systems [7]. It is, however, also relevant in the study of serial and parallel circuits, which are of interest here. TL allows the user to activate either a serial or a parallel circuit and to display all possible transition processes in real time (figure 7 and 9).

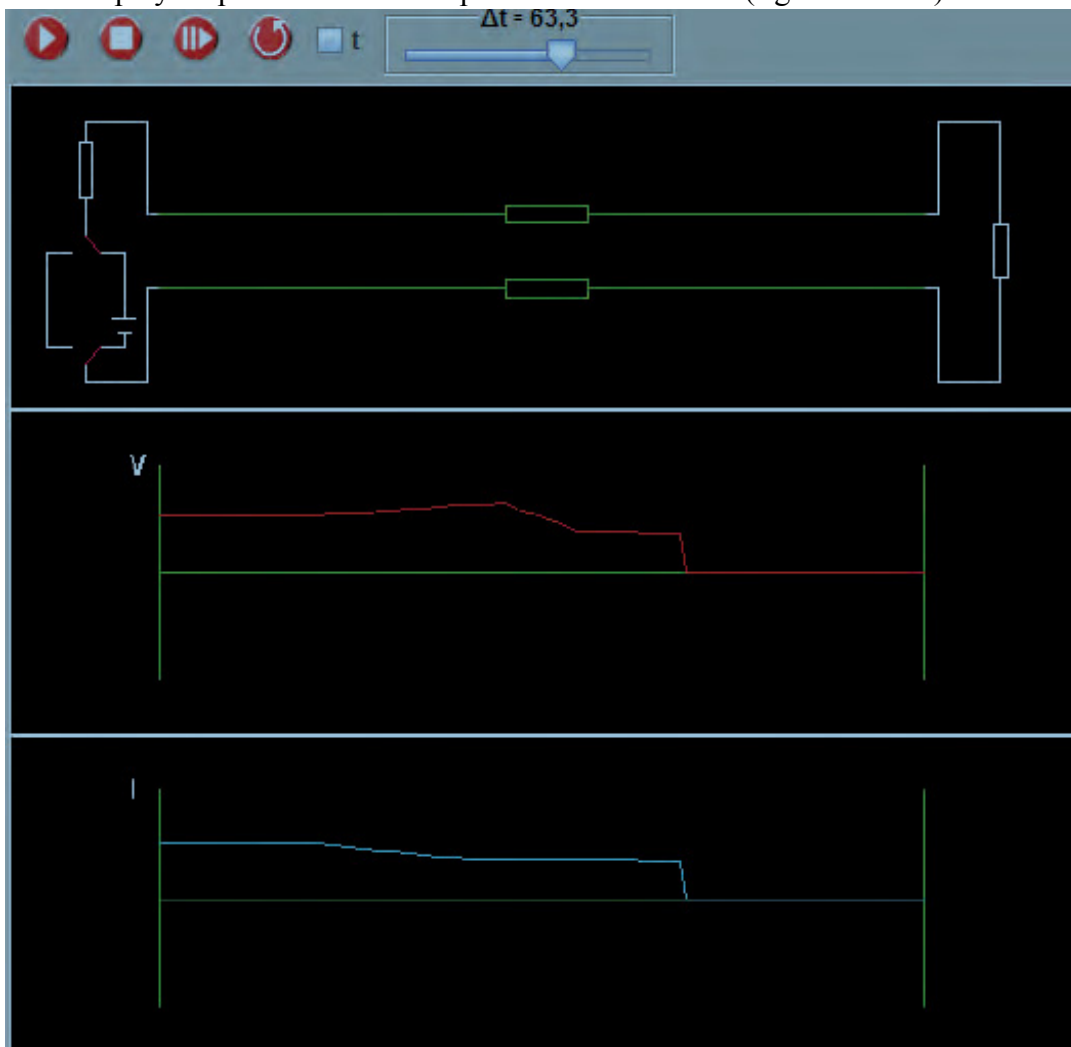


Fig. 7. Transition process for a serial circuit (resistors on both lines plus load).

The two symmetrically arranged resistors in the middle of the twin line and the load resistor at the end form a serial circuit with variable resistors. Reflection processes will occur upon impact of any current / voltage slope which can be traced until a final stationary state is reached.

A further visual support for understanding and concept development is given by a display of

voltage and current conditions in the form of arrows along the line (figure 8).

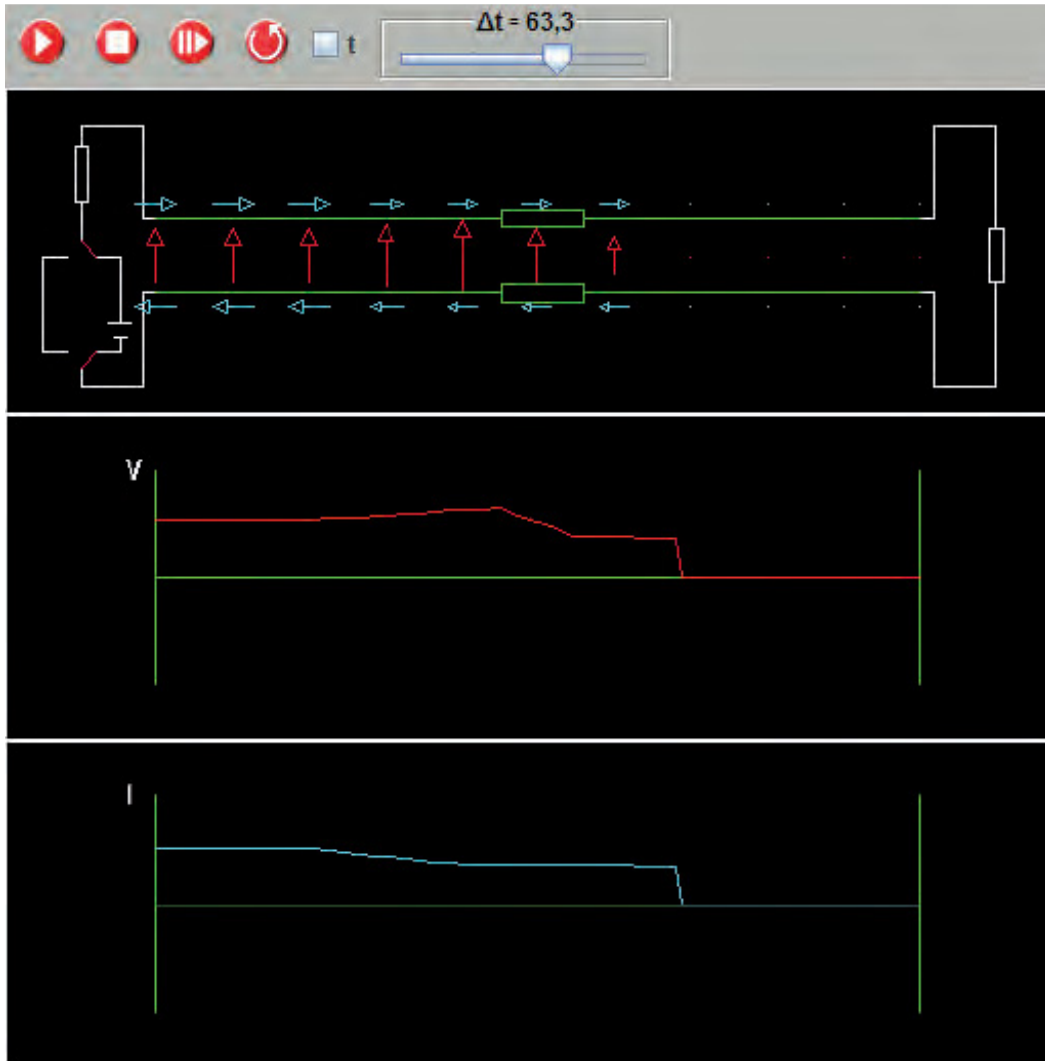


Fig. 8. Indication of direction and strength of the electric field (red) and intensity of current (green) along a twin line.

The resistance in the middle of the twin line can be replaced by a conductive area between the two lines of limited width and variable resistance. Together with the load at the end of the line, this configuration represents a parallel circuit, in which all ongoing transition processes can be

monitored until steady states are reached (figure 9).

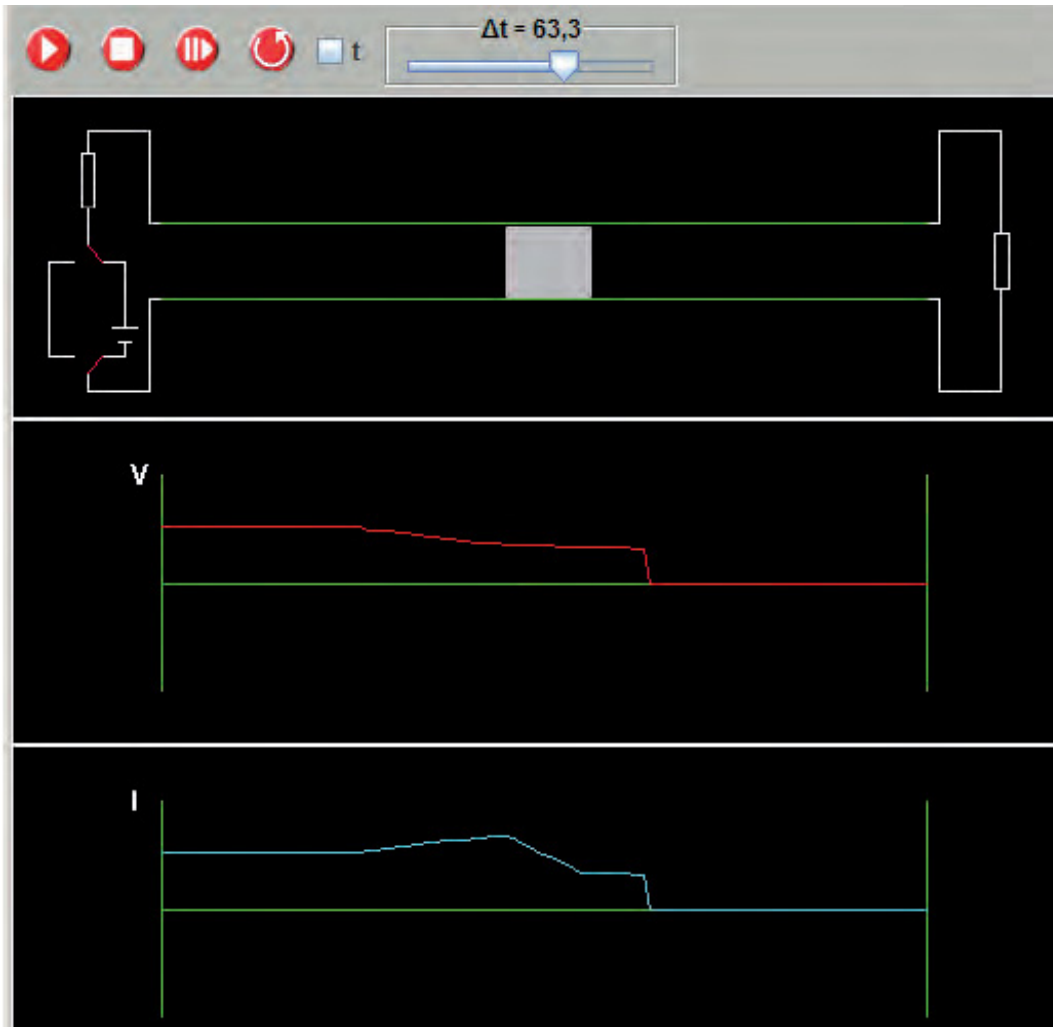


Fig. 9. Transition processes along a parallel circuit (Conductive region between both conductors plus load).

3. Conclusion

The electrical circuit in practical use is a very simple system. In general, it is sufficient to know whether or not a voltage is applied, and whether a current is flowing; the computation of stationary states does not require particular mathematical skills.

However, the task of explaining and understanding how the electric circuits actually functions is challenging.

Energy is transferred via force and motion and not via energy enriched matter. The consequences of this energy transfer and the basic relations of the system must be understood.

Students must recognize why surface charges build up on each current carrying conductor and why these surface charges in interaction with the conduction electrons are responsible for the flow of a constant current and the possibility that a steady state can be achieved.

Finally, students must understand that stationary states cannot exist without transition processes, whose characteristics should in principle be known.

Which of these aspects of the behaviour of a circuit should be selected for class study, and in what detail should they be studied?

This question can be compared to the one mentioned in an earlier article [8] about the degree of difficulty for an exercise in mountain climbing. When do we ask too much and risk failure; when are we too timid and risk loss of motivation? Such decisions can be taken only by a moun-

tain guide who is familiar with all the potential sources of danger and can provide all necessary assistance in critical situations.

The transfer to the physics classroom and to the necessary requirement for physics teachers is left to the reader.

4. Literature

- [1] H. Härtel et.al. Test about Voltage - A Basic Term in Electricity. Results.
http://www.astrophysik.uni-kiel.de/~hhaertel/Spannung/voltage_test_result.pdf
- [2] A video showing this experiment is found under:
<http://www.astrophysik.uni-kiel.de/~hhaertel/PUB/lamp-capacitor.htm>
- [3] H. Härtel. The so-called Simple Electric Circuit; Computer supported course material.
http://www.astrophysik.uni-kiel.de/~hhaertel/index_e.htm
- [4] H. Härtel; S. Divjak. Simulationsprogramm CLOC - Conceptual Learning Of Circuits. Documentation:
http://www.astrophysik.uni-kiel.de/~hhaertel/CLOC_doc/CLOC_doc_uk/index.htm
- [5] The idea to use the third dimension for visualizing potential differences was also use by-Tony Minich: Conceptualizing Series and Parallel Circuits Through 3-D Modeling. Phys. Teach. 43, 448-451 (2005). Such hands-on activity may be more impressive for students than computer simulations, but is certainly time consuming and lacking adaptability.
- [6] H. Härtel; E. Martin; F. Esquembre: Simulations programm TL -Transmission Line; Documentation:
http://www.astrophysik.uni-kiel.de/~hhaertel/TL_doc/TL_doc_uk/index.htm
- [7] H. Härtel; Transition Processes in Linear Systems:
http://http://www.astrophysik.uni-kiel.de/~hhaertel/index_e.htm
- [8] Entry to be decided depending on the kind of publication of the article about „The so-called simple electric circuit“