An analogical simulation for teaching electric circuits: a rationale for use in lower secondary school

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Abstract
Understanding simple electric DC circuits often represents a great challenge to many students in lower secondary schools. As a result, students’ knowledge of this subject is often dominated by alternative conceptions, even after instruction. One of the reasons for these learning difficulties is the intangibility of key physical quantities and concepts of electric circuits such as the electric potential or the electric current. A potentially effective way of making circuits more accessible to students in introductory electricity lessons represents the use of analogies or models. However, as a brief review shows, there is no single analogy or model that is ideally suited to foster an understanding of all key aspects of simple DC circuits. In order to address this issue and help learners develop a mental model of circuits, a new analogical simulation of simple electric circuits was developed. The simulation is suited for use in combination with the bike chain and the air pressure analogy and aims to support students’ development of a qualitative

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understanding of potential difference and current in circuits as well as a treatment of circuits as a connected system. Teachers and students can access the 3D simulation free of charge using a modern browser via www.marblemodel.com.

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1. Alternative conceptions of electric circuits

Developing a qualitative understanding of electric circuits represents one of the most challenging tasks in secondary school science [1]. Even after instruction, many students only have a vague understanding of so-called ‘simple’ DC circuits [2]. Despite their teachers’ best efforts, students often struggle to develop a coherent understanding of the relationship between current, voltage and resistance in electric circuits [3]. Instead, students’ thinking in this domain is often dominated by alternative conceptions. Although these may be useful in everyday thinking, they stand in opposition to the accepted scientific perspective [4, 5]. Furthermore, these alternative conceptions have proven to be stable mental structures, that are, in many cases, resistant to instruction [6]. Over the past decades, physics education research identified, analysed and documented various alternative conceptions on electric circuits [7]. Although their categorisation is not an easy task as they are often interrelated, a number of alternative conceptions have proven to be particularly persistent and widespread in various international studies [1, 2, 4, 8]. Among these common alternative conceptions are the following:

(a) The belief that the electric current is (at least partially) ‘used up’ by devices such as lamps and that this ‘current consumption’ is proportional to the device’s resistance (e.g. in a series circuit) [4, 9, 10].

(b) The belief that an ideal battery provides a constant current rather than a constant potential difference across its terminals [3, 11]. Students who hold this pervasive alternative conception often tend to ignore the role of voltage when analysing circuits and instead tend to reason exclusively with current and resistance [3].

(c) The belief that voltage is a property of the electric current (rather than an independent physical quantity that refers to two points in a circuit) [12, 13].

(d) The belief that the electric current, starting at one terminal of the battery, travels around the circuit element by element [2, 12, 13]. Rather than reasoning holistically, students often think that the electric current splits evenly at any junction irrespective of the resistors in the rest of the circuit (local reasoning) or believe that changing an element in a circuit only affects the parts of the circuit that are ‘downstream’ of the element in terms of the direction of current flow (sequential reasoning).

Despite diverse reasons for these conceptual difficulties, they can, at least partly, be explained with the abstract nature of the key concepts and physical quantities of electric circuits, all eluding direct perception. In order to facilitate students’ understanding of electric circuits, teachers and textbooks often use models and analogies in introductory electricity lessons [14].

2. Models and analogies in science education

In science education, the use of models and analogies is widespread, as they can be used as an effective instructional tool [15]. As illustrated in figure 1, an analogy acts as a tool to bridge two domains in order to link abstract ideas from the target domain (in our example electric circuits) to more familiar ideas from the source domain (e.g. a bike chain). More precisely, an ‘analogy’ corresponds to the relation or mapping of objects, attributes and their relationships between the source and the target domain. Consequently, an analogy should enable students to make inferences about an unknown or abstract target domain based on a
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Figure 1. An analogy represents the relationship of objects and attributes (represented through different shapes) between the source and the target domain. As illustrated, both domains do not necessarily match in every respect.

familiar and well understood source domain [16]. The use of analogies in physics teaching thus represents an inherently constructivist approach to learning as students’ actively construct new meaning on the basis of their prior knowledge [17]. However, the effective use of analogies in science education not only presupposes that both domains share a common structure, but also that the source domain is sufficiently familiar to students [18] and that they do not hold alternative conceptions in the source domain [17]. As shown in figure 1, the source and target domain do not necessarily match in every respect, which may also lead students to make wrong inferences about the target domain. It is therefore imperative that the choice of source domain is made carefully. Key structures and relationships suitable for the learning goals must correspond in both domains; in other words, the domains should ideally be isomorphic. Accordingly, analogies have been described as ‘double edged swords’ in science education research [19]. On the one hand, they can undoubtedly be an effective instructional tool to facilitate students’ conceptual understanding [15]. On the other hand, however, they may provoke misunderstandings or reinforce certain alternative conceptions.

3. Review of two useful analogies

Water circuit analogies of the electric circuit are widespread in science teaching [14]. Although the ‘flat’ water circuit analogy is very structurally similar to an electric circuit from a physical perspective, students are not sufficiently familiar with the source domain. In particular, they do not have a conceptual understanding of water pressure in closed water pipe systems. As a result, it has been shown that students struggle to understand that a water pressure difference causes the water flow just as potential differences cause a charge flow in circuits [20]. Furthermore, empirical studies show that students have similar alternative conceptions on closed water circuits as they have on electric circuits, examples of which are sequential reasoning, current or water consumption or the belief that the battery or pump represents a source of constant (water) current [20–22].

Given these findings and the not exclusively positive nature of analogies in science education in general, two more promising educational analogies that aim to illustrate the relationship between voltage, current and resistance in electric circuits are briefly reviewed in the following section: The bike chain analogy and the air pressure analogy. For each of the two analogies, the
guiding question shall be whether there are identifiable structural similarities between the source and target domain and whether high school students can be expected to benefit from it, given:

(a) Their prior knowledge in the source domain.
(b) Their typical alternative conceptions, as described above.
(c) Empirical findings from physics education research, where available.

Based on the review, we will present a newly developed computer simulation that can be used in combination with the discussed analogies as well as others (e.g. the water circuit analogy). In particular, the simulation aims to build on the strengths of the bike chain and air pressure analogy in order to enable students to develop a better conceptual understanding of electric circuits.

3.1. The bike chain analogy

The bike chain analogy compares the electric circuit with a bike chain. Here, the driving force at the pedals corresponds to the electric voltage, the speed of the chain links corresponds to the electric current, and the brake pads rubbing against the chain correspond to the electric resistors (see figure 2). As a bike chain is a highly visible component of bicycles, most students should have a good understanding of the source domain from their everyday life [23].

The analogy therefore represents an excellent way to illustrate certain key concepts of the electric circuit (see figure 2) [24]. For example, it is well suited to illustrate the concept of current, as students can easily count the number of chain links that move past a given point in a given time. Similarly, the analogy should be ideally suited to address the notion of current consumption because it demonstrates to students that although the chain links move around the circuit, they are not ‘used up’ by the brake pads. Furthermore, the analogy clearly illustrates to students that the electric circuit is an interconnected system, since, for example, applying the brake pads to the bike chain at one point immediately reduces the speed of the entire bike chain. The analogy is therefore also ideally suited to challenge students’ tendency to sequential and local reasoning [23].

However, the analogy has its limitations when it comes to more complex circuits with parallel branches (see table 1) [25]. Another clear limitation of the analogy lies in the fact that it only provides students with a very rudimentary concept of voltage as the ‘driving force’ of the electric current. In particular, it does not illustrate that voltage as a potential difference always refers to two points in a circuit as the physical quantity ‘voltage’ is not visualised in the analogy. Similarly, the analogy may not help learners understand

![Figure 2. The bike chain analogy of electric circuits.](image)

| Table 1. Suitability of the bike chain analogy in fostering an understanding of key aspects of simple DC circuits. |
|--------------------------------------------------|
| The bike chain analogy supports students…       |
| In understanding that the electric current is not consumed | Yes |
| In understanding that a battery is a source of constant p.d. | No |
| To understand that voltage refers to two points in a circuit | No |
| To understand that the electric circuit represents an interconnected system | Yes |
| In understanding parallel and mixed circuits | No |
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Figure 3. Colour coding the electric potential in a simple DC circuit as suggested in [30] in order to help students recognise potential differences in circuits.

Table 2. Suitability of the air pressure analogy in fostering an understanding of key aspects of simple DC circuits.

| The air pressure analogy supports students… |  |
|-------------------------------------------|--|
| In understanding that the electric current is not consumed | No |
| In understanding that a battery is a source of constant p.d. | Yes |
| To understand that voltage refers to two points in a circuit | Yes |
| To understand that the electric circuit represents an interconnected system | No |
| In understanding parallel and mixed circuits | Yes |

that an ideal battery represents a constant voltage source rather than a constant current source.

3.2. The air pressure analogy

The air pressure analogy aims to provide students with an intuitive understanding of potential and potential difference as well as the relationship between potential difference and current by drawing on their experiences with air pressure. In this analogy, the electric potential corresponds to air pressure or the so-called ‘electric pressure’ in the wire while voltage corresponds to an air pressure difference or the so-called ‘electric pressure difference’ that is applied to an electrical device [26]. A key advantage of this analogy over the closed water circuit analogy is that students are familiar with the source domain from their everyday life [27]. Based on first-hand experiences with air pressure, e.g. in air mattresses or bicycle tires, students can learn that just as air pressure differences lead to an airflow, voltage as an ‘electric pressure difference’ leads to an electric current, e.g. through a lamp [28]. By colour coding the ‘electric pressure’ in the wires [29] as shown in figure 3, students can easily identify potential differences in series, parallel and mixed circuits and recognise that voltage—as an ‘electric pressure difference’—refers to two points in a circuit (see table 2). Furthermore, colour coding the electric potential clearly illustrates to students that the battery represents a source of constant voltage rather than constant current [30].

Research findings show that a curriculum based on the air pressure analogy in combination with colour coding leads to fewer alternative conceptions and fosters a better conceptual understanding for the cause-and-effect relationship between voltage and current. However, research also shows that the analogy does not promote holistic reasoning about circuits any better than traditional instruction, possibly because the current itself, e.g. in the form of moving electrons, is not visualised at all in the analogy [8]. For the same reason, it is also rather unlikely that the analogy itself helps students understand that the electric current is not ‘used up’ in lamps (see table 2).

4. Simulations in science education

One of the objectives in teaching a topic in physics is that the learners develop a mental model, capable of describing phenomena as set out by given learning objectives. As mentioned previously, one difficulty in teaching electric circuits is the intangibility of the key physical properties. One effective way to remedy this is to visualise these quantities. This can be done by representing the properties as a static diagram, as can be seen in figure 3. However, the effectiveness of the visualisation for learning can be improved by integrating it into an interactive computer simulation [31]. In addition to the possibility...
of integrating movement into an on screen representation, one possible reason for increased effectivity, from a theoretical perspective [32] maybe increased engagement or interactivity. The addition of an interactive element also allows learners to test hypotheses. This allows for more opportunities for development of a mental model and varied use in different pedagogical methodologies in the classroom. Although conclusive experimental verification of how engagement is affected is not available, evidence suggests that increased interactivity produces higher learning gains [33]. What however is clear, is that where simulations were added to replace or enhance previously non-digital materials, learning outcomes were improved [33, 34].

5. A free three-dimensional simulation of simple DC circuits

Summarising the considerations above, it can be said that neither the bike chain analogy nor the air pressure analogy are ideally suited to help students overcome all of the typical alternative conceptions described at the beginning. It is therefore advisable that learners engage with more than one analogy to illustrate different aspects of the electric circuit. However, it might be a challenge for learners to develop a coherent mental model of the electric circuit based on different analogies [35]. For this reason, a new computer simulation was developed that aims to combine the advantages of the bike chain analogy with those of the air pressure analogy in combination with colour coding. The simulation can be accessed free of charge via www.marblemodel.com.

A key advantage of the simulation is that both current and voltage are visualised simultaneously, enabling students to distinguish between these two important concepts that are all too often confused. Furthermore, the computer simulation was designed to help students reason about circuits holistically, to visualise that voltage refers to two points in a circuit, to illustrate that the electric current is not used up in lamps and to demonstrate that an ideal battery constitutes a source of constant voltage rather than constant current (see table 3). For this purpose, the electric current is visualised by beads (representing ‘charge packets’) lined up like on a string of pearls, moving concurrently through the circuit, analogous to a bike chain. In contrast to other popular simulations that only illustrate the flow of charge while neglecting a specific visualisation of the electric potential (e.g. the PhET simulation ‘Circuit Construction Kit’ [36]), these moving beads, just

Figure 4. Colour coding the electric potential in a parallel circuit and showing the electric current with concurrently moving beads in the simulation.
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Figure 5. A parallel circuit in the ‘diagram mode’.

like the pipes in which they are located, are colour coded based on the electric potential of the respective part of the circuit (see figure 4). If a switch is added to a branch of the parallel circuit, it can easily be demonstrated that a battery is a source of constant voltage but not constant current.

A decisive advantage of the simulation compared to physical models (e.g. water circuits, bike chains or 3D-printed height models [37]) is that different circuits can easily be drawn up in order to quickly analyse key physical quantities in the circuit, e.g. potential differences. At the beginning, users either draw their own simple DC circuit in the ‘diagram mode’ (see figure 5) or select one of the premade circuits available in the simulation. These preconfigured circuits can easily be modified by adding new circuit elements. Using the ‘lab mode’, the circuit can then be visualised in a way that resembles a real circuit (see figure 6). This visualisation gives students the opportunity to work out the potential differences and currents in the circuit themselves.

In the ‘simple mode’, the electric potential in the circuit is visualised using colour coding as shown in figure 7. This mode aims to help learners identify potential differences in circuits. In combination with the air pressure analogy, this should allow them to develop a better understanding of the cause-effect relationship between voltage and current in circuits. For example, if a lamp has the same colour on the right and left, it is clear that no voltage is applied to it and, as a result, no current flows through it (see lowest bulb in figure 7). A parallel circuit can be easily identified using the colour coding, by recognising that each lamp is enclosed on opposite sides by the same two colours—red on one side, white on the other (see the upper two bulbs in figure 7). At this stage, the pipes are still closed to focus the students’ attention on potential differences. However, the pipes can partially be opened so that students can observe the beads moving at different drift speeds in order to provide them with a qualitative idea of the electric current in the various parts of the circuit. By zooming in on lamps, students can also observe that the current is not ‘used up’. The direction of movement of the beads corresponds to the physical direction of the current.

Users can freely move around in the 3D simulation, change the voltage of the battery and open or close switches. As each interaction, such as activating a switch, has an immediate effect on the beads’ movement and the colour coding in the entire circuit, learners are encouraged to reason about electric circuits holistically. Furthermore, it is possible to earth individual sections of the circuit. The simulation also offers the option of representing various components of the electric circuit, such as the battery, in a particularly
**Figure 7.** Illustrating potential differences using colour coding in the ‘simple mode’ to facilitate a better understanding of the cause-effect relationship between voltage and current.

**Figure 8.** Child-friendly visualisation of a battery and a lamp.
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The newly developed 3D simulation...

| Illustrates that the electric current is not consumed | Yes |
| Illustrates that a battery is a source of constant p.d. | Yes |
| Illustrates that voltage refers to two points in a circuit | Yes |
| Illustrates the electric circuit as an interconnected system | Yes |
| Illustrates parallel and mixed circuits | Yes |

Table 3. Suitability of the newly developed simulation in fostering an understanding of key aspects of simple DC circuits.

child-friendly way, which may be attractive to younger students (see figure 8).

6. Conclusion and outlook

Understanding electric circuits often represents a great challenge to many students. One of the reasons for these learning difficulties with electric circuits is that the underlying physical quantities and concepts are not directly observable. A potentially effective way of making circuits more accessible to students in introductory electricity lessons represents the use of analogies or models. However, there is no single analogy or model that is ideally suited to help students overcome all of the alternative conceptions on circuits that they typically hold. The simulation presented in this article aims to combine the strengths of the bike chain analogy and the air pressure analogy by, on the one hand, visualising the electric current in the form of concurrently moving beads similar to a bike chain, and, on the other hand, using colour coding to visualise potential differences in circuits. However, the simulation can also be used in combination with other analogies as the colour coding may also stand for the value of water pressure (e.g. in the ‘flat’ water circuit analogy), the height (e.g. in the open water circuit analogy) or the tensile stress (in the bike chain analogy). In future, it is planned to add support for new components such as capacitors, coils and diodes so that the simulation can also be used for more advanced topics. The 3D simulation runs in modern browsers and can be accessed free of charge via www.marblemodel.com.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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