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RESEARCH ARTICLE

Investigating High School Students' Ideas About Energy Transfer in Simple Electric Circuits

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State of the literature

- Students' ideas and misconceptions about electrical circuits have been well documented in past studies. However, the topic of energy transfer in electrical circuits is not often addressed.
- Past studies have identified and described different energy frameworks to categorize students' ideas about energy.
- Demonstration interviews have been used by previous studies to gain insight into the students' understanding of the physical processes of an experiment.

Contribution of this paper to the literature

- This study shows that most of the interviewed secondary school students were not able to describe the process of energy transfer within an electrical circuit in a scientifically correct manner.
- We were able to identify different energy frameworks to categorise the students' answers, two of which have not been described by previous studies.
- This paper includes a documentation of all the students' drawings when asked to indicate the direction of energy transfer in a simple electric circuit, which can be used as a basis for future research.

Abstract

In a recent study, nine students, aged 16-17 years, from Vienna, Austria have been interviewed about energy in electrical circuits. This paper reflects on one part of the study focusing on questioning students about the process of energy transfer. The research design and method involved semi-structured interviews with demonstration experiments, in which the students were asked to observe, describe and explain the experiments. The analysis of the interviews revealed the difficulties students faced in explaining the role of energy and drawing the path of energy transfer in electrical circuits. The paper presents the different energy frameworks described by previous studies that have been used by the students and discusses the inconsistencies in their reasonings. The findings emphasize the need for suitable teaching materials to promote students' understanding about energy and energy transfer in electrical circuits.

Keywords

energy transfer, energy frameworks, interviews, qualitative study, demonstration experiments

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Introduction

Understanding electrical circuits is fundamental in physics education, with previous research extensively documenting students' misconceptions in this area (e.g. Engelhardt & Beichner, 2004; Trumper & Gorsky, 1993). However, there remains a significant gap in addressing the concept of energy transfer within electrical circuits.

While literature has outlined various energy frameworks used to categorize students' conceptions (Watts, 1983), exploration of the understanding of energy transfer has been limited. This gap in research is particularly noteworthy given the broader significance of learning about energy in physics education. A fundamental understanding of energy and energy transfer not only contributes to advanced scientific inquiry and future pursuits in fields like engineering, but also has practical implications for understanding everyday processes, such as how energy can be transferred to a smartphone from a wireless charging pad.

In the Austrian physics curriculum, energy education unfolds across different stages. Initially introduced in lower secondary school (grades 7 and 8) alongside thermodynamics and electricity, energy concepts resurface in upper secondary education (grades 10 and 11) during the 6th year, alongside discussions on power, batteries, and photovoltaics. Subsequently, in the 7th year of secondary school, a more comprehensive exploration of energy occurs, including topics such as conventional and alternative energy sources, energy transmission, and safety in handling electrical energy (BGBl. Nr. 88/1985). Although energy evidently plays an important role in the Austrian physics curriculum it seems that students do not develop a fundamental understanding of this topic and specifically the topic of energy transfer in electrical circuits by the end of their school career.

To gain more evidence on this matter, this study aims to assess student difficulties in understanding energy in electrical systems and to compare them with existing research on energy frameworks to provide insight into the current status quo. By focusing specifically on the topic of energy and energy transfer in electrical circuits, this research addresses a critical gap in the literature and tries to formulate implications for future research.

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Theoretical framework

Students' difficulties about energy transfer in simple electric circuits

When examining students' understanding across various topics, it is important to acknowledge the ongoing discourse surrounding terminologies used to refer to students' difficulties, that are incorrect from a physicist's point of view (diSessa, 1993). These terminologies are often intertwined with different theoretical frameworks and perspectives: Two contrasting viewpoints are commonly described as 'knowledge as theory' (Chi, 2005; Vosniadou, 1994) and 'knowledge as elements' (diSessa, 1993; Hammer, 2000).

Historically, a significant portion of the physics education research literature has framed student reasoning within the 'knowledge as theory' framework, characterizing student ideas as 'misconceptions' or 'alternative conceptions' – coherent frameworks of ideas persistently present in students' minds, that hinder instructional efforts (Clement, 1982; Hestenes et al., 1992).

In opposition, the 'knowledge as elements' framework represents a more modern model, suggesting that student ideas include flexibly combinable 'knowledge pieces' that can be activated independently or in networks, with activation depending upon the situation. This perspective underscores the dynamic nature of student cognition (diSessa, 1993). Within the 'knowledge as elements' viewpoint, the displayed difficulties reflect students' inappropriate or simplified reasoning patterns, which originate from using basic reasoning elements called phenomenological primitives (p prims), which are in themselves neither correct nor incorrect (diSessa, 1993).

While both frameworks may manifest among students, in this study, we cannot definitively determine whether students' responses reflect stable misconceptions or dynamic, context-dependent knowledge pieces. Hence, it is imperative to view existing literature to determine if similar ideas and notions have been documented among students' responses and to find out whether further research in this field is necessary. In this paper, we choose to use the term 'student difficulties' to encompass all student responses that deviate from a physicist's perspective.

Previous research has shown that many students (even at university level) hold on to persistent but scientifically incorrect ideas about simple electrical circuits, even when they have been taught about them in school (Stetzer et al., 2013). There are many well documented student difficulties about simple electric circuits, especially regarding current, voltage and resistance, as well as geometrical thinking that have been researched thoroughly in the past (Ivanjek et al., 2021; Johsua & Dupin, 1985; McDermott & Shaffer, 1992; von Rhöneck, 1986).

However, student difficulties about energy in simple electric circuits are less frequently documented. There are some studies that focus on energy frameworks in general, which are also, though not exclusively, applicable to electrical contexts, and studies that focus on energy frameworks in simple electrical circuits (while also addressing other concepts such as current or voltage). A study conducted by Trumper and Gorsky (1993) applies to this first category. They describe different energy frameworks, such as anthropocentric energy – the idea that students associate energy with human beings – that are not necessarily limited to electrical contexts. The second category includes student difficulties that are directly set in an electrical context. An example would be Engelhardt and Beichner (2004) research, who conducted a study on students' understanding of direct current resistive electrical circuits. They discovered that the main source of difficulties for students can be linked to a confusion of different terms as they "(…) assign the properties of energy to current, and then assign these properties to voltage and resistance" (Engelhardt & Beichner, 2004, p. 106).

The physics behind energy transfer in electrical systems

Describing the energy transfer in electrical systems is not a simple task and requires looking into the complex principles of electromagnetism. While our paper focusses on the difficulties students encounter with this topic, it is essential to give an overview of the correct scientific framework for reference. From our observations, there appear to be various approaches to teaching this topic in schools, but many of them do not accurately describe the physics behind energy transfer in electrical systems. However, Henry Poynting proposed an elegant mathematical approach to discuss this topic, providing a theoretical foundation for understanding energy transfer in electrical systems that can be adapted and used in school settings.

According to Poynting, energy is transmitted in electrical systems by electromagnetic fields. This can be described with the Poynting vector (Poynting, 1884):

$$\vec{\mathbf{S}} = \frac{1}{\mu_0}\vec{\mathbf{E}} \times \vec{\mathbf{B}}$$

This vector quantifies the power per unit area carried by electromagnetic waves, with its direction indicating the flow of energy. Although there is a scientific consensus about this, the idea contradicts the expectation that the flow of energy must take place in the wires of a simple electric circuit (Sefton, 2002).

Galili and Goihbarg (2005) explain that the transfer of energy from the energy source to the electrical device (e. g. a lamp) in an electric circuit is primarily facilitated by the electromagnetic fields in the space surrounding the conductors (see **Figure 1**). This concept challenges conventional expectations but aligns with experimental observations and theoretical frameworks. In essence, the energy source provides surface charges, which distribute around the wires of the circuit and create an electric field, pointing from the positive to the negative surface charges (Chabay & Sherwood, 2007; Jackson, 1996). When the circuit is closed and a current flows through the conducting wires, a magnetic field is induced around it according to Ampère's law

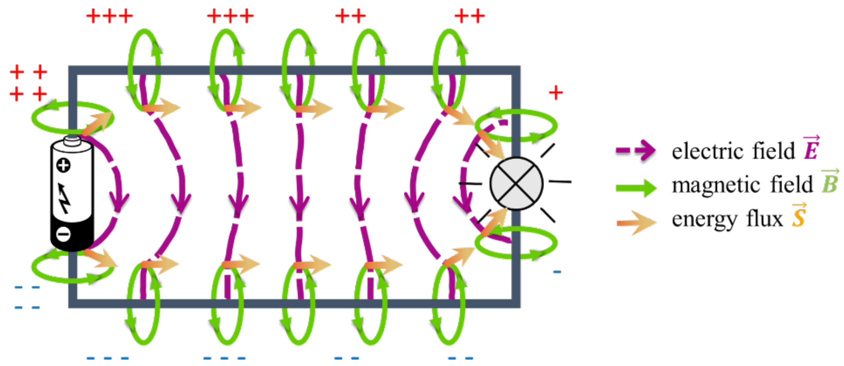


Figure 1. Representation of the electric field, magnetic field and energy flux in a simple electric circuit, consisting of a battery, wires and a light bulb (Winter, 2023).

(Griffiths, 2024). The combination of the electric and the magnetic field surrounding the circuit facilitates the propagation of the energy flux through space, rather than solely within the confines of conductive materials (Sefton, 2002).

Detailed accounts of the surface charge distribution in circuits with simple geometries, which are fundamental for understanding the electric field, and consequently, the electromagnetic field and energy flow, can be found in references such as Hernandez & Assis (2003) and Davis & Kaplan (2011). For the analysis of more complex geometries, Härtel's work (1987) offers valuable insights.

Energy frameworks found in the literature

To gain a deeper understanding of students' difficulties regarding energy transfer within electrical circuits, it is crucial to review existing literature about this topic first. Pilser's (2023) work provides an overview of different energy frameworks that are relevant in the context of electrical circuits. In the following section of this paper, we present six of these documented energy frameworks, which form the baseline of our analysis.

1) Energy as a transferable fluid (Watts, 1983):

In this framework, students conceptualize energy similar to a fluid substance, often drawing analogies to rivers or flowing currents. They describe energy transfer as a fluid-like flow, particularly emphasizing electron movement.

2) Conduction of energy (Behle & Wilhelm, 2017):

Students adopting this framework focus on the role of conductive materials, particularly wires, to explain the process of energy transfer. They describe energy flow in terms of conduction through these materials, emphasizing the circular path from the battery to the light bulb and back again. Unlike the fluid analogy, the emphasis here is on the conductivity of the materials rather than the fluid-like nature of energy itself.

3) Partially transferred energy (Behle & Wilhelm, 2017):

This framework suggests that energy transfer is not complete, with some energy being converted into other forms while a portion returns to the source. Students using this perspective often describe how energy is 'used up' at the energy converter, such as the light bulb, with only a fraction of it returning to the battery. This perspective acknowledges the conversion of energy into other forms, such as heat or light, during the transfer process, reflecting a more nuanced understanding of energy dynamics within a circuit.

4) The scientific framework (Trumper & Gorsky, 1993):

Within this framework, students perceive energy transfer as a direct process from the source to the energy converter. They understand that energy can be converted from one form to another, such as electrical energy into light or heat energy. Unlike other frameworks, there is less emphasis on the nature of energy or its movement through materials. Instead, students focus on the scientific principles underlying energy transfer and conversion, reflecting a more abstract understanding.

5) Produced energy (Watts, 1983):

In this framework, energy is viewed as a product of processes, often associated with the generation of waste products like heat, radiation, or emission gases. Students conceptualize energy generation as a by-product of various mechanisms or activities, with surplus energy being produced.

6) Energy as a catalytic converter (Behle & Wilhelm, 2017):

Within this framework, energy is perceived as a driving force or catalyst for various processes or activities. Students understand that without energy, these processes would not be possible. This perspective reflects a more abstract understanding of energy, viewing it as a facilitator of change or action within a system. It emphasizes the role of energy in enabling various phenomena to occur, highlighting its fundamental importance in driving physical processes.

Research design and methods

The objective of this study (Pilser, 2023) was to identify current student difficulties in the observed population on the subject of energy, and more specifically energy transfer, in electrical systems and to compare them with existing research on energy frameworks (e.g. Behle & Wilhelm, 2017; Watts, 1983). To achieve this aim, the following research questions were devised:

(1) To what extent can specific energy frameworks, as outlined in the literature, be identified within the responses gathered from interviews?

(2) What alternative ideas about energy and energy transfer in electrical circuits can be found amongst the students' answers?

Participants

To answer these research questions, we conducted nine semi-structured interviews with upper secondary school students aged 16-17 years in Vienna, Austria. This age group was purposefully chosen for two main reasons: Firstly, these students had been previously exposed to electricity education during their schooling years, having received instruction on the subject in grades 7, 8, and 10. Secondly, this age group typically aligns with the period when energy and energy transfer concepts are introduced in physics curricula.

The interviewed students attended five different schools in Vienna, Austria and the sample included students with a range of interests and grades in physics.

Research Context

As we aimed to identify specific energy frameworks amongst the students' answers, we decided to use the method of demonstration experiments (Jelicic et al., 2017). There were two primary reasons for this choice: Firstly, it allowed us to adhere to a familiar pattern that mirrored the structure of the students' physics lessons, including an observation, a description, and an explanation of the observed phenomena. Secondly, the semi-structured nature of the interviews provided us with the opportunity to delve deeper into the students' reasoning and thought processes while still adhering to our predefined questions. This flexibility enabled us to prompt students to elaborate on their statements or to clarify their perspectives, thereby providing us with additional details during the analysis of the interviews.

The demonstration experiments consisted of simple electric circuits with varying components. Initially, the circuit included a flat battery, a light bulb and two wires. In the first variation, the battery was replaced by a small generator. In the second variation, the light bulb was replaced by a small fan. Finally, two identical circuits including batteries and small light bulbs were examined, differing only in their power, which was initially unknown to the students. For each variation, the students were asked to observe, describe, and explain the experiments.

This pattern aligns with the Predict-Observe-Explain (POE) approach, which is recognized for its efficacy in promoting active learning and conceptual understanding (Driver et al., 2000). In line with POE, before each demonstration, students were prompted to make predictions about the outcomes of the experiments, observe the actual outcomes, and then explain the observed phenomena using scientific principles and concepts.

The focus of this study was on energy transfer. Therefore, at the end of each experiment, the interviewees were also asked to describe the role of energy in the respective circuit and to indicate the 'path of the energy', i.e., to describe and sketch on a circuit diagram how and where the energy is transferred (see **Figure 2** and **Figure 3**).

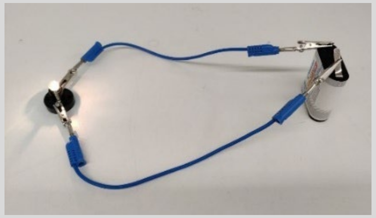
1	In this experiment, you see a simple electrical circuit, consisting of a light bulb, a battery and two wires. The circuit is not yet closed, i.e. not all the wires are correctly connected to all the components of the circuit. 
1.1	What do you think will happen when the circuit is closed? (The circuit is closed by the instructor)
1.2	What can you observe? Try to describe the experiment as precisely as possible!
1.3	Can you explain the experiment and your observations? Why does the light bulb shine?
1.4	What role does energy play in this circuit?
1.5	How is the energy transferred to the light bulb? Please draw a sketch!
1.6	Can you name the law of conservation of energy? Does it apply to this example?

Figure 2. Representation of the electric field, magnetic field and energy flux in a simple electric circuit, consisting of a battery, wires and a light bulb (Winter, 2023).

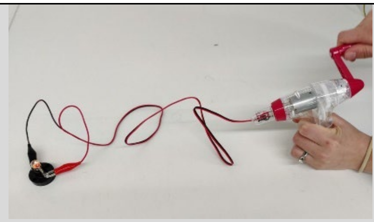
2	We will now change the simple electric circuit slightly. Instead of the battery, we will install a small generator that you can turn by hand. 
2.1	Will the light bulb shine without a battery?
2.2	What can you observe? Try to describe the experiment as precisely as possible!
2.3	Can you explain the experiment and your observations? Why does the light bulb shine?
2.4	What role does energy play in this circuit?
2.5	How is the energy transferred to the light bulb? Please draw a sketch!

Figure 3. Representation of the electric field, magnetic field and energy flux in a simple electric circuit, consisting of a battery, wires and a light bulb (Winter, 2023).

Data Analysis

Development of Codes and Categorization Schema

The interviews were transcribed and analyzed using the qualitative content analysis approach (Mayring, 2015). The students' answers were systematically coded using a newly developed categorization scheme. Initial codes were based on a literature review on various energy frameworks (see theoretical framework section above).

In some cases, the students' answers included more than one energy framework, therefore more than one code had to be assigned. Additionally, there were some cases where none of the literature-derived codes appeared suitable, leading to the development of new codes.

Interrater Reliability

To ensure consistency across analyses conducted by different researchers, an assessment of interrater reliability was undertaken. Approximately 10% of the dataset was independently coded by another researcher specializing in physics education, using the established coding scheme. The calculated Cohen's Kappa value was 0.86, which falls within the 'almost perfect' range according to established literature standards (Landis & Koch, 1977).

Findings

This paper will focus on the results of questions 1.4-1.6 (see **Figure 2**) and 2.4-2.5 (see **Figure 3**), as they aim at the students' understanding of energy transfer in electrical circuits. The following table provides an overview of the number of students and the coded energy frameworks in their answers:

The results of the interviews show that all interviewed students had major difficulties with this topic as indicated by their varied use of energy frameworks and notable inaccuracies in describing the energy transfer process.

Item 1 – The Simple Electric Circuit

During question 1.4. and 1.5 students were asked to explain what role energy plays in the given simple electric circuit, consisting of a light bulb, a battery and two wires. Additionally, they were asked to draw the path of the energy on a sketch and explain their answer.

The majority of the interviewees (six out of nine) drew the path of the energy flow along the wires of the circuit (see **Figure 4**, which shows an example from the interviews) from one side of the battery to the light bulb and back to the other side of the battery. However, the students used different energy frameworks for their reasoning.

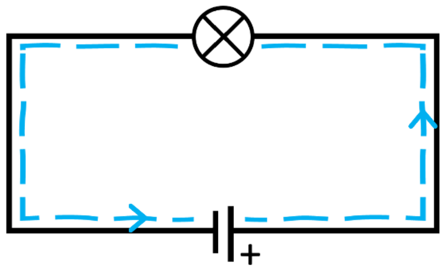


Figure 4. Energy flow diagram in a circuit (Interview 5). Note how the energy flows from one side of the battery to the light bulb and back to the other side of the battery again.

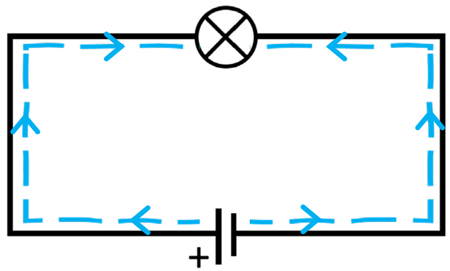


Figure 5. Energy flow diagram in a circuit (Interview 8). Note how the energy flows equally from both sides of the battery to the light bulb.

The other students drew the path of the energy from both sides of the battery to the light bulb (see **Figure 5** for an example from the interviews). Similar to the first group, the energy flow was described close to the wires or within them.

During the analysis of this interview item, four energy frameworks could be identified within the students' answers. In some cases, more than one energy framework was applicable. As can be seen in **Table 1**, the student answer from IP7 included both the conduction of energy as well as the scientific framework.

The energy as a transferable fluid framework, the partially transferred energy framework and the scientific framework have been described by previous studies (deductive coding). Only the conduction of energy framework was added in this study (inductive coding), as no evidence of this framework could be found in the literature by the authors of this study.

Table 1. Energy frameworks used by the interviewed students (IP) in item 1.5 and 2.5.

Energy framework	Item 1.5	Item 2.5
Energy as a transferable fluid	IP2, IP5	
Conduction of energy	IP1, IP3, IP4, IP7, IP8	IP2, IP7
Partially transferred energy	IP6, IP9	IP3, IP5
The scientific framework	IP7	IP8
Energy consumption and conversion		IP6
Produced energy		IP9
Energy as a catalytic converter		IP4

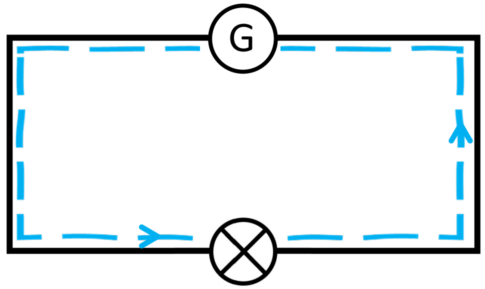


Figure 6. Energy flow diagram in a simple electric circuit with a generator, two wires and a light bulb (Interview 8). Note how the energy flows from one side of the generator to the light bulb and back to the other side of the generator again.

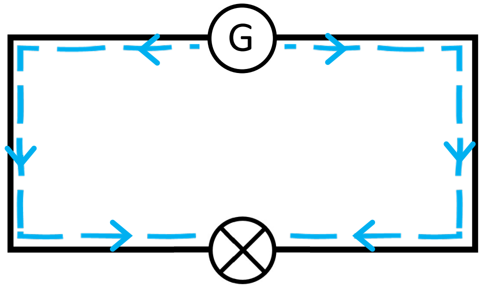


Figure 7. Energy flow diagram in a simple electric circuit with a generator, two wires and a light bulb (Interview 2). Note how the energy flows equally from both sides of the generator to the light bulb.

Item 2 – The Hand Generator

In this item, students were presented with a simple electric circuit consisting of a small hand generator, a light bulb and two wires (see **Figure 3**).

In questions 2.4 and 2.5, similarly to item 1, students were asked to describe what role energy plays in the electric circuit and how the path of the energy could be drawn and explained. This item was added later and therefore only administered to eight students.

Five of these students sketched the energy flow along the circuit's wires (see **Figure 6**), from one side of the generator to the light bulb and back to the other side of the generator. However, the underlying reasoning behind this depiction varied among the students and different energy frameworks were used in their explanations.

The answers of the remaining three students were of a different nature. One student illustrated the path of energy flow from both sides of the generator towards the light bulb (see **Figure 7**).

As a result, two students encountered a conflict when considering the possibility of energy returning to the generator. In their viewpoint, the energy itself is already transformed through the hand generator, and the light bulb ceases to shine when the generator is no longer cranked. This led them to question the plausibility of energy going back to the generator, resulting in a sequential view (see **Figure 8** and **Figure 9**).

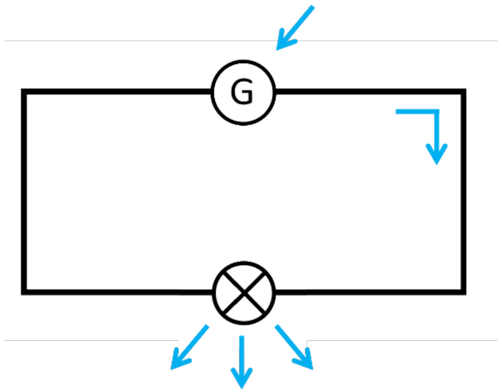


Figure 8. Energy flow diagram in a simple electric circuit with a generator, two wires and a light bulb (Interview 7). Note how the energy flows from the generator, through the wires towards the light bulb and does not return to the generator again. It is converted into another form of energy at the light bulb.

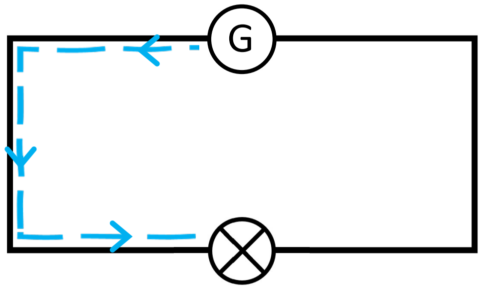


Figure 9. Energy flow diagram in a simple electric circuit with a generator, two wires and a light bulb (Interview 9). Note how the energy flows only from one side of the generator through one wire to the light bulb and not back again.

The students' answers were analyzed and overall, six energy frameworks could be identified. Again, in some cases, more than one energy framework was coded (see **Table 1**).

During the analysis of the second item, three more energy frameworks could be found: the produced energy framework, the energy as a catalytic converter framework and the energy consumption and conversion framework.

The first two have been described by previous studies (deductive coding) and the third was added to this study (inductive coding), as we could not find documentation of it in our literature research.

Inconsistencies in students' reasoning

Note how inconsistent the reasoning is amongst the students if you compare item 1 and 2 (see **Table 1**). Only IP2 continued to use the same energy framework in their reasoning but all the other students changed their viewpoint. An example would be student IP3, who used the conduction of energy framework in their reasoning for item 1 and the partially transferred energy framework for item 2.

These inconsistencies suggest that the documented student difficulties are not stable constructs, often referred to as deep structures, but rather current constructions, that are used by students in a concrete situation (Niedderer & Schecker, 1992).

Discussion

The Energy Frameworks

The following section describes the different energy frameworks, which could be identified in the students' reasonings.

1) Energy as a transferable fluid (Watts, 1983)

Students who used this framework described energy as a fluid-like substance. It is associated with electron movement. One student (IP5) described energy as follows: "It's a river, you could say. Like a river, it just flows through [the wires] and then back [to the battery]. But if I only connect one [wire to the battery], then it doesn't work, because then the energy doesn't turn on." In this reasoning it is evident, that the student assumes that the energy is a fluid-like substance that flows to the light bulb and back to the battery again (see **Figure 4**).

2) Conduction of Energy

Similar to the first framework, there was another line of argumentation which described that the energy would flow in a circle from the battery to the light bulb and back again. However, in this case the focus was not on the idea of energy as a fluid but on the conductive material, in particular the metal of the wires. One student gave the following description: "This would be the battery. (…) [The energy would flow] along the wire to the light bulb. Then energy is being used up here [at the light bulb] and the energy that remains flows [back] through the wire [to the battery]." (IP4)

The students who chose this energy framework would also draw something similar to **Figure 4**. One thing that is essential for this framework and that distinguishes it from the previous one is that the wires are mentioned several times, which implies that they are seen as an important element for the energy transfer.

3) Partially transferred energy (Behle & Wilhelm, 2017)

This framework describes the transfer of energy locally. According to this idea, most of the energy is 'released' at the energy converter and converted into heat, radiation, movement, etc. However, part of the energy moves back to the energy source. One student (IP9) stated that some of the energy "gets used up" at the light bulb and some travels back to the battery. This is explained as follows: "because that also has something to do with 'useful' energy. A little bit [of the energy] is used up [by the light bulb] and only what is not needed is sent back [to the battery]. (…) Let's say from 100 Joules only 90 [J] are being used [by the light bulb] and around 10 [J] go back [to the battery] again. It [the energy flow] starts at the positive terminal [of the battery] and more [energy] comes out [of the battery] than comes back."

This reasoning suggests that energy is lost at the light bulb through energy conversion and potentially during transport, but only for a certain timeframe, as long as there is enough energy available.

It is important to note however that when directly asked about the conservation of energy (question 1.6), the students clarified that this loss or consumption of energy meant a conversion into other types of energy such as heat. The fact that energy cannot really be consumed and always remains in the overall system was well known to most of the students.

4) The scientific framework (Trumper & Gorsky, 1993)

Students who chose this energy framework argued that energy is transferred directly from the energy source to the energy converter and can be converted from one form of energy into another.

One student (IP7) addressed this idea as follows: "(…) In the wire, this is where the electrons flow. This [the light bulb] is where some of the energy is emitted and this is where we can then see the photons [light] and [the electrical energy] is probably also converted into other forms of energy, like heat energy (…)." Within this framework, the electrons, if they are mentioned, move around the circuit in a circular motion and are not 'used up' at the energy converter. Some students mention that they carry the energy to the energy converter but not back again. Students who answered with this framework would draw a sketch similar to **Figure 5**. It is important that the energy flow is drawn around the wires, not within them.

5) Produced energy (Watts, 1983)

In this framework, energy is viewed as the product of a process, whether it be a singular mechanism or a series of ongoing (energy production) processes, or an incidental by-product of the primary process. It is generated internally and released externally. Due to the utilization of only small quantities, a surplus of energy is generated. Students who used this framework often linked energy to waste products such as smoke, sweat, radiation, or emission gases.

One student (IP9) used this framework to describe the process of energy transfer in the second item with the hand generator. In their reasoning, the student claimed that "(…) the entire energy is being used up by the electrical device, because one generates as much [energy] as is needed".

The respective sketch can be seen in **Figure 9**. The student sketched the energy flow from the generator towards the light bulb. In their justification, only one wire was necessary for the energy flow, neglecting the prerequisite that a circuit must be closed in order for energy transfer to take place.

6) Energy consumption and conversion

Students who utilized this framework often used the terms energy consumption and energy conversion interchangeably. Although the students seemed to know the fact that energy is converted into a different form, in their viewpoint, it is lost for the energy source. This implies that only the energy source, such as a battery, consumes or loses energy.

Student IP6 used this framework to describe the process of energy transfer from a hand generator towards a light bulb: "Then I draw it [the energy flow] back in the same direction and along the cable and back towards hand generator. This [energy] is probably also lost somehow (…)".

The student who used this framework drew a sketch similar to **Figure 6**, depicting the energy flow along the wires towards the light bulb and back to the generator again.

7) Energy as catalytic converter (Behle & Wilhelm, 2017)

In this framework, students believe that energy acts as a driving force or catalytic converter for processes or activities. Without it, these processes would not be possible. Energy is understood in a very abstract way.

This is evident in the answer from student IP4. In this response, the student describes the role energy plays in a simple electric circuit. Energy is understood as a means "to make the lamp light up. From the movement, from the transformer into the cables to the lamp and from the other cable back again." This student came up with a sketch similar to **Figure 6**.

Key Takeaways

The findings of this study show that students have different ideas about the process of energy transfer. Each interviewee used at least one energy framework or a combination of multiple frameworks to justify their answers. However, none of the students were able to give a scientifically correct answer that remained consistent throughout the interview.

Furthermore, we were able to document different students' ideas on how energy transfer takes place in a simple electric circuit by analyzing their drawings. These results give several key insights into students' understanding of energy transfer in electrical circuits:

Firstly, we observed that all interviewed students struggled to come up with a consistent argumentation of how energy can be transferred in a simple electric circuit. Students were not able to explain that energy transfer takes place through electromagnetic fields in the space between the wires and they would often adapt a line of argumentation that includes energy flowing through the wires of a circuit. This diversity in students' reasoning highlights the complex nature of understanding the topic of energy transfer and the importance of addressing it with suitable teaching materials in school.

Secondly, some students seem to struggle with the basic knowledge surrounding simple electric circuits such as identifying that an electric circuit must be closed in order for it to work. This might contribute to the confusion regarding the topic of energy transfer. We feel that this basic knowledge is crucial for the students to be able to solve more complex tasks, such as describing the role energy plays in a simple electric circuit.

Thirdly, the mentioned student difficulties manifested themselves in the use of different energy frameworks, which were mostly consistent with previous research on this topic (see 'theoretical framework' section above). Additionally, two new energy frameworks were identified during this study: the Energy Consumption and Conversion framework and the Conduction of Energy framework. However, further research is needed to explore the relevance of these new energy frameworks for research and teaching.

Moreover, our study sheds light on an underexplored aspect of student difficulties regarding energy transfer within electrical circuits. Notably, there appears to be a lack of research specifically dedicated to addressing this context. While our theoretical framework section references existing studies that extensively explore misconceptions about electrical circuits, specifically concepts such as current, voltage and resistance, we were not able to find studies that focused on the exploration of student difficulties about energy transfer in electrical circuits. Hence, this study fills an existing gap in the literature by documenting on student difficulties related to energy transfer in electrical circuits.

Considering the insights from this study, future research could benefit from incorporating alternative educational approaches, such as the Observation Experiment, Explanations, Verification Experiment and Application Experiment approach used in the ISLE project (Halloun & Hestenes, 1985), to potentially enhance students' performance and understanding in physics learning activities.

Limitations

There are certain limitations to this study that must be considered.

Firstly, the study's sample size does not allow us to make any generalizations about the observed energy frameworks. We do not suggest that every energy framework can be found in every classroom. However, it can be helpful to know about some possible student difficulties before teaching about energy transfer in electrical circuits in secondary school.

Secondly, while the interrater validity turned out to be very high, there were some cases when disagreement between the raters could be observed initially. This was due to the fact, that for most student answers more than one energy framework could be identified.

This highlights a fundamental point: the responses provided by students appear to be dynamic, current constructs, that change over time.

Thirdly, this study did not document on individual differences, such as varying levels of motivation or specific interests in the field of physics amongst the students. However, these factors might have impacted the results of the study.

Conclusion and Implications

This study contributes to the understanding of high school students' difficulties with the concept of energy, and more specifically, the process of energy transfer in simple electric circuits.

The energy frameworks from previous studies, that are described in this paper, could be confirmed through our student interviews. Additionally, two new energy frameworks could be identified. These results offer a valuable resource for physics educators facilitating a deeper understanding of students' struggles when learning about energy in electrical circuits.

In addition, the analysis of the students' drawings of the direction of the energy transfer in electrical circuits, that have been documented in this paper, sheds light on how diverse students' perspectives and reasonings are. This could be a great starting point for future research with a greater sample size.

The findings of this study emphasize the need for targeted instructional material to address student difficulties and foster a deeper understanding of energy transfer in schools. For this reason, a project has been initiated at the University of Vienna which aims to develop new teaching material on the topic of energy transfer. The goal is to create a curriculum design for high school level that effectively supports students in understanding the basics of energy transfer in simple electric systems.

Moving forward, the insights from this research serve as a baseline for future endeavors aimed at refining science education practices. With a clearer understanding of students' difficulties in the field of electrical circuits, educators are better equipped to develop tailored interventions and lesson plans.

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