Weatherby, Thomas Sean

Talking circuits. The development and assessment of a digitally-scaffolded, collaborative method for teaching and learning electrical circuits in early secondary schools

Berlin : Logos Verlag Berlin 2025, 316 S. - (Studien zum Physik- und Chemielernen; 394)

Studien zum Physik- und Chemielernen
M. Hopf und M. Ropohl [Hrsg.]
394

Thomas Sean Weatherby

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Studien zum Physik- und Chemielernen

Herausgegeben von Martin Hopf und Mathias Ropohl

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Martin Hopf und Mathias Ropohl

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Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

Logos Verlag Berlin GmbH 2025

ISBN 978-3-8325-6008-9
ISSN 1614-8967
DOI 10.30819/6008

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Georg-Knorr-Str. 4, Geb. 10
D-12681 Berlin

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https://www.logos-verlag.de

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The Development and Assessment of a Digitally-Scaffolded, Collaborative Method for Teaching and Learning Electrical Circuits in Early Secondary Schools

Thesis for the award of the Degree of Doctor of Natural Sciences presented to the Faculty of Physics of the Goethe University, Frankfurt am Main, Germany by

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Born in Oxford, England, United Kingdom.

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(D30)

The open access publication of this book was funded by the Open Access Publication Fund of Goethe University Frankfurt am Main.

Accepted as a thesis by the Faculty of Physics at the Goethe University Frankfurt.

Dean: Prof. Dr. Roger Erb

Reviewer: Prof. Dr. Thomas Wilhelm

Date of Viva Voce: 16th April 2025

Heartfelt thanks to everyone who has helped along the way.
To Mum and Dad, my deepest gratitude, for all the chats, proofreading and heavy lifting, without which I could never have completed this project.
To my mentor, Thomas, whose trust, responsiveness and assistance supported my work and, moreover, made it worth doing.
To Jan-Philipp, whose openness and enthusiasm made both starting in Frankfurt and starting a doctorate a much less of a daunting task.
To all of my colleagues in Frankfurt, with whom the jokes, chats and shared purpose made eating the Mensa food worth it.
To BERA-BJET, for the funding.
To the teachers, with whom I worked during my intervention, who took me in with open arms and made me feel part of the team within days.
And lastly, to the learners, for taking it in their stride.

Contents

List of Figures

List of Tables

1 Foreword

Perhaps the most remarkable aspect of evolution is its ability to generate cooperation in a competitive world. Thus we might add "natural cooperation" as a third fundamental principle of evolution beside mutation and natural selection.

– Martin Novak
Five Rules for the Evolution of Cooperation

1.1 Motivation

I firmly believe that the best way to get on is by cooperation. The story of science is often told through the triumph of great geniuses or singular breakthroughs. But, most science is done in teams. This could be in projects like the LHC in CERN, involving thousands of different scientists and engineers from all over the world, or several teams working on small aspects of the same research or in the team of largely uncredited deaf women who were responsible for tracking and cataloguing stars under Edwin Hubble. Even above being a "team game", science is in itself a great shared reality, based on observations and measurements. This, in turn, is based on a shared philosophy, the scientific method: hypothesis, testing and falsification. To construct this shared reality and effectively share their ideas and receive feedback, scientists share their work through written publications and spoken presentations, containing diagrammatic representations of data and concepts[1]. However, scientists working in teams mostly communicate by talking to each other within their research communities[2].

When talking to one another about science, a specific vocabulary is needed. This vocabulary too is co-constructed. This was made very apparent to me when I joined a largely German-speaking laboratory in Munich during my Master's studies. When laser beams in the laboratory needed to be aligned, the German speaking members of the team would not use the German word "ausrichten" to talk about alignment. Instead, as there were a large number of non-native speakers in the international team, the made-up word "alignen"[3] would be used by the whole team, to facilitate understanding. Depending on who was operating the laser, they would need to align something specific, for their experiment. So, depending on who was saying they were going to align the laser, it would mean a different concrete set of actions achieving the same thing: alignment. This throwaway example allows us to see the adopted use of a specific word in a single context, used to mean subtly different things. Not to mention if I was talking to the same people about different topics, then the word alignment could mean something totally different, e.g. politically aligned or alignment in a role-playing game[4].

However, it is not always the case that scientific language enables accessibility. In fact, it can have quite the opposite effect. The everyday word that is used to discuss household electricity in English and German are "power" and "Strom" respectively, the literal translation of "Strom" into English is "current". Learners continue to use both "power" and "Strom" in the context of science lessons when they are not appropriate and associate them with similar misconceptions[5]. For this reason we

[1] There are of course other incentives to do these things, as they garner prestige and a kind of scientific social capital.
[2] There is often considerably less social capital at stake in these kinds of interactions, which can indeed make them more informal and more effective!
[3] Simply the English verb align with German conjugation rules
[4] For the uninitiated, whether your character is good or evil or follows the rules or not.
[5] A discussion of what misconceptions are, how they work, other names for them and

need to make our scientific vocabulary accessible to our learners, if we want to strive for equal and effective education. Science educators cannot also ignore the fact that they are introducing learners to a culture of science. This includes its language and despite the temptation to have a separate scientific language that engages with abstract thought, learners must be exposed to all given words in a variety of contexts and meanings must be made explicit and related to their context.

Using this language in productive classroom talk comes with its own benefits. Students participating in a talk rich curriculum have improved outcomes across the core subjects in primary school[6]. A famous example of the power of student talk to improve learning progress in Physics, comes from the world of higher education with Peer Interaction[7]. Here, undergraduate students engaged in discussions during their contact time, increasing their conceptual understanding. An example of this kind of intervention in lower secondary electricity, however, was not as successful in increasing learning outcomes[8].

With these thoughts in mind, I wanted to go about designing and assessing learning materials that would benefit practitioners and learners alike and be confident in making my recommendation (or otherwise!) of them, but not be solely driven by testing outcomes.

Things did not go exactly to plan. Working across borders in schools, during a global pandemic, as the UK tries to figure out how to leave a customs union that you want to bring 30 iPads from, is not an experience I would recommend. Nonetheless, the following is the collection of ideas, results and analysis collected over those very enjoyable, nearly six years.

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how to try and combat them see Chapter 2.

[6] Jay et al. [2017]

[7] Mazur [1997]

[8] Ruthven et al. [2017]

2 *Theory and Measurement of Learning and Knowledge*

You see my physics students don't understand it...
That is because I don't understand it. Nobody does.

– Richard Feynman
QED: The Strange Theory of Light and Matter

Chapter Contents

In this Chapter, I will begin by giving an overview of relevant learning theories, paying special attention to definitions needed in this chapter and beyond. As is generally the case, the chapter will develop from general to specific, from descriptions of knowledge and learning intended for general use to specific learning challenges faced in the teaching of science, specifically physics, and then even closer, on the topic of electricity, the topic of the intervention study in this thesis. The chapter concludes with a review of the literature on the specific alternative conceptions on the topic and the available concept knowledge test on the topic of electricity.

2.1 Models of Learning and Knowledge

Models of learning and knowing within Western philosophy date back to Aristotle's analogy of the mind as a blank slate waiting to have ideas etched upon it[9]. These have been developed throughout history and have become progressively more complex with focus on different aspects of the learners' development, with key contributions, that will be discussed in the opening to this chapter from developmental and cognitive psychologists such as Piaget, Vygotsky and Rogoff. Furthermore, there are science education specific contributions to models of mental organisation and cognitive change from educational specialists, such as Vosniadou and diSessa. The idea in this chapter is not to evaluate and critique these models of learning and cognition, but to introduce definitions[10] and use the ideas present within them to inform thinking about how to best support teaching and learning within the context of lower secondary physics, on the topic of electricity. These ideas go on here and in later chapters to inform the rationale and decision making processes involved in developing materials as discussed in Chapter 4. Where models, however, may might make contrary suggestions for practice, this is discussed.

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[9] Smith [2014]

[10] Those who read this with a background in the learning sciences will probably be familiar with the ideas contained in this section. I present this here to be an introduction to those with background in physics, from a more "practical" teaching background or for readers who come from a different cultural context.

2.1.1 Piaget's Mental Representations

Schemata describe "figurative representations"[11], suggesting a type of mental image, for clustering and discriminating objects into particular classes or groups. These groupings have underlying rules and rest upon generalisations. The schema are constructed and adjusted by attempted *assimilation* of new ideas into pre-existing schemata and the *accommodation* of small changes to these schemata[12] where inconsistencies lead to cognitive *dissonance*[13].

Schemes are, similarly, mental representations, but this time for procedural knowledge, i.e. how to do certain tasks. This study is primarily concerned with developing figurative knowledge, however the scheme of work implemented introduces some procedures for analysing electric circuits. More nuanced descriptions of the way learners' mental structures are conceptualised are given in Section 2.1.6, as developing and measuring these is the centre of my study. However, just conceptualising them in this primarily rational way ignores the social dynamics important for an intervention centred around peer work.

2.1.2 Vygotsky's Social Learner

The importance of social interaction is central to Vygotsky's work and, although Piaget does not ignore its importance[14], it is not central in his writings. As the current study will implement discussion work in pairs, exchange in this *intermental* space[15] is central. Learners too not only construct ideas together, but in expressing their ideas through *externalisation*[16], mediated by *psychological or cultural tools*, they develop whatever (nascent) thoughts are present[17]. Learners then have the

[11] Siraj-Blatchford and Siraj-Blatchford [2010, p. 209]
[12] Piaget [1929] in Goddu and Gopnik [2022]
[13] Piaget [1929] in Adcock [2012]
[14] DeVries [1997]
[15] A social space for ideas between people.
[16] Piaget also illustrates an internalisation/externalisation dynamic, but on an operational level, with the identification of object surface features being mapped onto how the object may be used and causal constructions, for more see Martí [1996].
[17] Vygotsky [1986]

opportunity to become aware and reflect on their own ideas before interacting with *externalisations* from their partners, which, in turn, they may *internalise*, in a transformative process[18], after their negotiation in the *intermental* space[19].

Another key idea that will be important throughout this work, with regards to both technology and language, is the mediated nature of thinking and idea exchange through *psychological or cultural tools*, also called *signs* or *symbols* under which Vygotsky includes: "language; various systems for counting; mnemonic techniques; algebraic symbol systems; works of art; writing; schemes, diagrams, maps, and mechanical drawings; [and] all sorts of conventional signs"[20]. The idea of a *psychological tool* when looking at language, diagrams and technology will be especially key in my study. Vygotsky argues that usage of *psychological tools* result in new ideas, so in developing tools for classroom use it is important to ensure that these are conducive to the knowledge we wish to construct. For example, through careful use of language and analogy or in the production of diagrams or learning workflows, as discussed in Chapter 4. It is also of note that these tools are not inherent, and must too be learnt.

The Zone of Proximal Development defines the difference in what a learner may achieve when engaged in an activity alone, and when "under adult guidance or in collaboration with more capable peers"[21]. Their partner or guide enables the learner to generate and co-construct novel ideas and solve previously unsolvable problems. Learners can then *internalise* this and then be able to tackle similar activities alone. This, however, beyond Vygotsky, is also possible when the peer is not "more capable", i.e. neither peer can solve the problem alone. For

[18] Vygotsky and Luria [1930/1994] in Lawrence and Valsiner [1993]
[19] Vygotsky [1981b] in translation from Выготский, Лев Семёнович. Развитие высших психических функций: из неопубликованных трудов. Москва: Издателство Академии педагогических наук РСФСР, 1960.
[20] Vygotsky [1981a, p. 137] in translation from the same Russian source.
[21] Vygotsky [1978, p. 86]

example, a well detailed illustration of idea generation and convergence on the scientific principal of this nature is given in a secondary science context in Heeg et al. [2020]. This idea is relevant in that it helps us conceptualise the role of external support enabling the learner to develop, rather than this being modelled by some innate stages.

Beyond Vygotsky's ideas, the nature and extent to which this guidance is provided can be described using the metaphor of *scaffolding*[22]. The guidance suggested includes "recruitment of the child's interest in the task, establishing and maintaining an orientation towards task-relevant goals, highlighting critical features of the task that the child might overlook, demonstrating how to achieve goals and helping to control frustration."[23] These are reflected on in Chapter 4 on the development of teaching and learning materials, for example, through embedding physical contexts, prompting the learner through tasks and implementing a scheme of work and questioning in ways that slowly increases in difficulty. One caveat to this being that the teacher must play a role in all mediation of this kind as well. However, this aspect does not form the locus of interest in this study, with the principles of *scaffolding* being examined more through the teaching and learning resource provision, both analogue and digital - with special consideration being paid to digital affordances and peer learning. The adult role will be discussed, in the way in which technology can empower teachers to assess the outcomes of peer talk, enabling them to make small group or whole class level interventions depending on the outcomes. Empowering the teacher to intervene when necessary, whilst respecting learner autonomy.

2.1.3 Rogoff's Learning in Cultural Context

Whereas Vygotsky primarily looks at dyads, Barbara Rogoff emphasises the cultural nature of learning as a child's "apprenticeship in thinking" with adults or peers in a variety of group structures, her central concern is illustrated well in her own words:

[22] Wood et al. [1976] in Wood and Wood [1996]
[23] Wood and Wood [1996, p. 5]

> I [Rogoff] extend the concept of the zone of proximal development by stressing the interrelatedness of the roles of children and their caregivers and other companions and the importance of tacit and distal as well as explicit face-to-face social interaction in guided participation. The thesis is that the rapid development of young children into skilled participants in society is accomplished through children's routine, and often tacit, guided participation in ongoing cultural activities as they observe and participate with others in culturally organized practices.[24]

Whereas Vygotsky is concerned primarily with language, Rogoff looks too at "guided participation" in other means, by modelling and involving the learner in a non-verbal activity, hence the "apprenticeship" metaphor. She also puts more emphasis on the role of the learner who is seen to "seek, structure and demand assistance [...] actively observe social activities, participating as they can"[25]. Another big difference is that Rogoff suggests how to structure certain situations to facilitate guided participation. Beyond the description of the processes at hand, she is concerned with giving concrete practice recommendations for practitioners. However, her main consideration is not our setting, for this we rely on school focussed works later, for example Mercer [1995], Littleton and Mercer [2013a], Gaunt and Stott [2018].

Due to the intervention being at the level of peer talk, I am interested particularly in her discussion of peer dyads. Rogoff recognises the role a Piagetian model has for asymmetrical dyads[26], where a more able other introduces a model better matched to reality, inducing cognitive conflict in a partner. This is similar to the Vygotskian idea of the expert and the novice acting in the *zone of proximal development*, a convergence. Rogoff, however, states and evidences[27] that cognitive growth can be made in symmetrical dyads and even for the more expert learner in asymmetrical dyads, while also showing cases where no progress or regression have been made. The increases in task efficacy from working

[24] Rogoff [1991, p. 16]
[25] Rogoff [1991, p. 16]
[26] Where one learner is more expert than the other.
[27] Rogoff [1991, p. 173]

together may come from discussing differences in opinion[28], sharing ideas about the logic of the task[29] and being able to reach different levels of information recall through qualitatively different strategies[30].

The way in which the learning tasks in this study are designed, particularly the application workflow, is influenced by the way Rogoff discusses peer dyads, guiding each others' participation. For example, that learners are given space is seen as important, as evidenced by a study of a play-task with 5- and 8-year-olds in Brody et al. [1984], who see a significant reduction in the number of "task-related verbalisations", but an increase in the proportion of this type of verbalisation, due to the reduction in overall verbalisations, when an observer is present. Although these dyads are younger than the age group in this study, Brody et al. [1984, p. 1427] also state their "results suggest that younger children react less, or at least somewhat differently, to the presence of observers than do older, school-aged children. On the whole, however, the two age groupings responded in a similar fashion to the presence of observers.". This relative stability across ages indicates an effect worth considering with the year eights in the current study. Ideally, one would want to retain the high proportion of "task-related verbalisations" from the observed task, as well as, the high number of verbalisations from the unobserved task design, by finding a balance, as discussed in Section 4.5. In summary, here, like Rogoff, our goal is the "structuring of children's participation so that they handle manageable but comfortably challenging subgoals of the activity that increase in complexity with children's developing skill and understanding."[31]

2.1.4 *The Learner as Agent of Change*

All of the previous theories are focussed on the development of the learner rather on the part they can play in shaping their context. The

[28] Light and Glachan [1985]
[29] Damon and Phelps [1987] in Rogoff [1991]
[30] Rogoff cites Lomov [1978], but more modern, larger studies give a more mixed picture of recall style tasks c.f. Wiersema and van Oudenhoven [1992].
[31] Rogoff [1991, p. 18]

transactional model of development looks at the internalisation/externalisation as a bi-directional process and describes a model in which learners can have an impact on their surroundings, as illustrated the following quote from Sameroff [2009, p.8]:

> The transactional model stresses the plastic character of the environment and of the organism as an active participant in its own growth. In parallel with the cognitive revolution in psychology, it reflects a change from the stimulus-response learning theories that view the child's behaviour as simple reactions to environmental contingencies to the organismic-constructivist perspective in which children are thought to be actively engaged in attempts to organise and structure their world.

Conceptualisation of learning in this way is necessary for the implementation of effective assessment and feedback cycles, as well as how learners employ learnt *psychological tools* and encoding methods or digital tools to self-scaffold. Through formative assessment in the discussion phases as outlined in Section 4.4.2, the teacher is able to get information from the learners. The teacher then responds to this, making a pedagogical decision, by adjusting their teaching: reteaching not yet understood content or increasing tempo through well understood content. This is an example of how regulation of the learning process can be enabled through technology and the information exchange from learner to environment and then in turn from environment back to learner. With regard to the interplay between *psychological tools* and encoding methods, learners are taught how to encode potential with colours. The learner hence acts on the environment, colouring the diagram, which then acts as a *self-scaffold* enabling the learners to approach a more difficult aspect understanding a given circuit diagram, relying on the learner's agency to structure the environment around them in order to transform the task into something more approachable.

2.1.5 *Self Determination Theory*

All these theories, at least as discussed, relate to the development and modelling of concept knowledge gain. In this section learners' subjective experience is briefly discussed. This will be accounted for in the following study through *Self Determination Theory* from Ryan and Deci [2000], aspects of which are measured using the Intrinsic Motivation Inventory (IMI) from the same authors. The IMI examines intrinsic motivation and self-regulation, breaking these aspects down into six sub-scales: 1. interest/enjoyment, 2. perceived competence, 3. effort, 4. value/usefulness, 5. felt pressure and tension, and 6. perceived choice while performing a given activity. The IMI is used to examine three of these subscales (interest/enjoyment, perceived competence and felt pressure and tension) as a pre- and post-test. Effort, value/usefulness and perceived choice are all not measured, as I do not aim or expect to change any of these variables and the questionnaire should be kept as short as possible. As learning in peer dyadic discussion de-emphasises the role of the teacher and places them in a mediating role rather than a purely instructive one and discussion, as well as the use of the iPad to answer instead of a "hands-up" approach, *felt pressure and tension* is expected to decrease. The introduction of new technology and a variation of teaching methods may lead to increased *interest/enjoyment*, through a *novelty effect*. However, although as the intervention is longer than 8 weeks the *novelty effect* may be limited[32]. The outcome of *perceived competence* is harder to predict; the learners may have more opportunities to be confronted with information that produces *cognitive conflict* and yet they will also be able to play the role of *expert* with their peers rather than being positioned always as *novice* within the classroom.

2.1.6 Representations, Analogies and Models both Mental and Scientific

Representations, analogies and models form important building blocks for understanding physics and its pedagogy. However, the words are used both in educational and psychological settings, and often with subtly different meanings. Representations as used in Treagust et al. [2017a], a book specifically on Multiple Representations in Physics Education, uses it to mean a mode of representation for information, in this case about a physical system. A representation could be a verbal

[32] Clark and Sugrue [1991] in Chwo et al. [2018]

explanation, a diagram or an example of the phenomena at hand in form of a demonstration, among others. Rather than referring to something external, psychologists often use "representation" to mean an internal cognitive symbol[33], like the schemata or schemes discussed earlier. Or, even, as a set of four elements: "the thing being represented (object), the thing doing the representing (medium), the content of the representation (meaning) and the agent or system using the representation (user)"[34]. For clarity, I will avoid the use of the word, unless including clarifying specification.

The definition of model is a little more complicated. First, we have to distinguish mental models from scientific ones, once again dividing mental internality and externalilty respectively. Mental models are internal and "live in our minds" whereas scientific models are external and they are communicated with external representations[35], reflected previously when discussing Vygotsky's *internalisation* and *externalisation* processes. A naïve idea of a model might be that of a smaller version of a given object of system. A model boat, for example, proves an instructive case in Figure 2.1, a model boat has some structural similarities with a "real" boat. When we compare the real boat and the realistic model we see surface similarities, but fewer with the little tin boat. The little, tin boat, with its ability to propel itself along the water has a functional similarity with the "real" boat that the scale model does not have. These two types of similarities will play a key role in choosing analogies for teaching, as discussed in Section 4.3.3.

Physical models strive to represent different physical systems. The aim of them from the view of the scientific method is to make predictions about the system that they represent. However, from a pedagogical viewpoint the ideas behind them are compound. In science classrooms (and in fact in scientific endeavours more widely) models are not only used to predict, but frequently to explain. That is to say that there

[33] Morgan [2014]
[34] Cummins [1991] in van Rooij [2022]
[35] Epstein [2008] in van Rooij [2022]

Figure 2.1: Three Boats with Surface and Structural Similarities: Shown left to right are a real boat, a model boat that moves and a realistic looking model boat. Real and realistic model boat images uploaded to Wikimedia by Tim Reynaga and licenced under CC BY 2.5.

is a familiar phenomenon and a model is developed post hoc to give reasons as to why it is happening.

Analogies can be drawn between model and physical object[36] or between multiple models. In order to make teaching a given model easier, an analogy may be introduced, linking to a familiar or more intuitively understood model with that of a more abstract one. It is here the ideas of structural and functional similarity become useful again. For something to be a good analogy, for the purposes of teaching, there needs to be sufficient similarity between the source (the well known) and target (the to be taught) domain[37]. Importantly, all of the primary concepts to be taught must have an analogue that appears in the source domain. The way these concepts relate must also be analogous in both domains. Taken together this is appropriate *relational* matching. Learners also make connections between domains with mere-appearance (surface level) matching[38]. Furthermore, it can also be shown that superficial similarities are important for learners to connect the two domains[39], making it a desirable attribute for teaching analogies. As in Figure

[36] Kircher et al. [2015]
[37] Gentner [1983]
[38] Gentner and Markman [1997]
[39] Gentner et al. [1993], Gick and Holyoak [1980], Keane [1987] in Blanchette and Dunbar [2001]

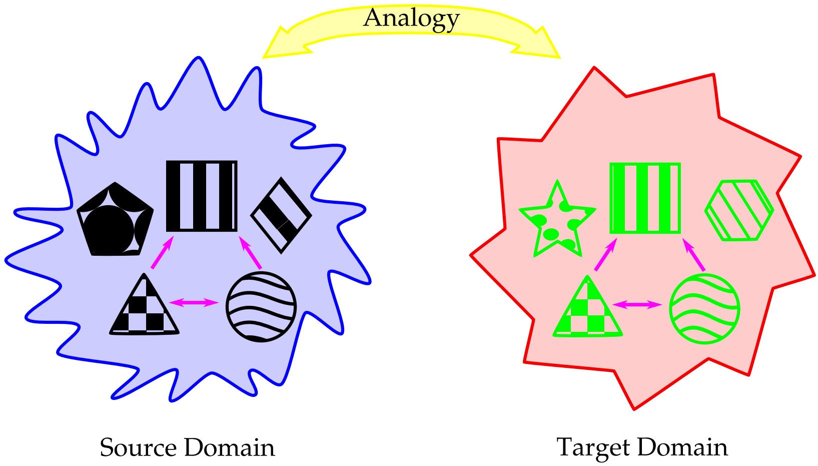

Figure 2.2: An analogy represents the relationship of objects and attributes (represented through different shapes) between the source and the target domain. As illustrated, both domains do not necessarily match in every respect. Author's work, published in Burde et al. [2021].

2.2[40], we can see the blue and red shapes represent the source and target domains respectively. There are specific features of the concepts represented by the square, circle and triangle in the target domain, that we want to teach, represented by their number of sides and patterns. We also want to teach the ways they relate to each other, represented by the arrows. To make this more concrete using ideas from the domain of electricity and its mapping to pressure, these three concepts could be current, resistance and potential difference, and the relations $R = \frac{V}{I}$, or the equivalent in words. In the domain of pressure, these are represented by airflow, blockages and pressure difference and the fact that a higher pressure difference results in a higher airflow and that blockages with reduce airflow. These relations and the teaching of them will be more explicitly addressed in Chapter 4. Note too, that

[40] Interestingly, an analogical structure for explaining analogies!

there are some features that are not the same, such as the colours of the objects or the shapes not linked by arrows. Of course, some of the features of the system will be different and this is to be expected. For example, to return to the previous examples that what flows changes between electrons and air, or that a battery works on a different basis to a normal air pump. As long as these do not represent core differences within our model to be taught, they can be addressed for interested learners, but do not impact our central learning objective. How one goes about effectively connecting these two domains, i.e. facilitating analogical learning, will be discussed also in Chapter 4.

2.2 *Conceptual Change*

The idea of conceptual change is useful in science teaching as it contrasts with learning of *declarative* or *procedural* knowledge, for which the routes of acquisition are relatively well established. *Conceptual Change* is deeper and more elusive and to examine it in this section we will draw on and extend the historical review by diSessa [2022]. *Conceptual Change* Theory's roots lie in two historical-philosophical works from Kuhn [1962] and Toulmin [1972] whose differences underpin the divergence in subsequently discussed theories within this section. In short, Kuhn [1962] discusses scientific theories[41] shifting in a period of radical change, switching between one theory and a new, *incommensurable* theory. *Incommensurable* meaning that the new theory's claims are unable to be expressed in terms of its predecessor. The transition between these theories happens rapidly, which Kuhn likens to Gestalt switches[42]. Toulmin [1972] undermines this, examining the lack of *systematicity* actually present in science. He uses the term *conceptual ecology*, looking at wider contexts as well as interaction between developing concepts. This describes a more complex types of knowledge and transitioning between concepts, contrasting with Kuhn's "binary" Gestalt switch.

[41] This is a discussion of scientific theory more broadly, not at the level of a learner.
[42] Like the immediate transition from seeing one image in an optical illusion to another.

2.2.1 Rational Conceptual Change

Posner et al. [1982] drew from both of the aforementioned works (among others) to define a set of four rational preconditions that must be met to engender *accommodative*[43] conceptual change:

1. There must be dissatisfaction with existing conceptions.
2. A new conception must be intelligible.
3. A new conception must appear initially plausible.
4. A new concept should suggest the possibility of a fruitful research program.

Their writings are heavily influenced by the history and philosophy of science, asserting that the learning process is "rationally based", looking to engender cognitive conflict through "anomalies" that do not fit learners' initial conceptions. They reflect that doing this, however, is difficult, as learners may not recognise the conflict the "anomalies" present to their own implicit ideas. They also question, that even if "anomalies" are presented and the theory understood, it remains "at best only intelligible and partially plausible, but never fully persuasive to students who are firmly committed to a set of conflicting metaphysical beliefs and epistemological commitments"[44]. They do not, however, expect such an "anomaly" to be rejected outright. For example, in an intervention where experiments were used to create *cognitive dissonance* in learners, learners said that the experiment was wrong or broken in several ways, or even "accused [the teacher] of "falsing"[sic] the experiment"[45], perhaps indicating the need for the inclusion of affective factors into the description.

Posner et al. [1982] formulate a set of further recommendations, for content as well as teaching strategy and teacher role. Logically, ensuring learning has first taken place, before trying to cover more content and that learners be taught "observational theory" along side to enable

[43] in the Piagetian sense (defined in 2.1.1)
[44] Posner et al. [1982, p. 224]
[45] Johsua and Dupin [1985, p. 336]

engagement with the included "anomalies" are advised as ways to structure content necessary for this style. The teacher's role is envisioned as quite combative, they confront learners with anomalies, diagnose and deal with errors diagnosed, as well as, regularly challenge "*ad hoc*-ness" or inconsistencies in learners' thinking, in order to engender the desired cognitive change. Interestingly, they also recommend uses of "metaphors, models, and analogies... [to] ... make a new conception more intelligible and plausible", which could be seen as an *assimilation* (as opposed to the *accommodation*-al style of learning they are outlining) into an existing schema. Because, for analogical learning to be successful, a good *source domain*, i.e. an existing schema, needs to exist in order to be extended (see previous section).

There is no detailed description of the internal representations or to the mechanism, other that it is a piecemeal, but complete, overhaul of the concept. The mechanistic description happens at a concept and claim level, the process of conceptual change being described as learners' "process of taking an initial step toward a new conception by accepting some of its claims and then gradually modifying other ideas, as they more fully realize the meaning and implication of these new commitments"[46]. This does not, however, look at finer granularities of representations and does not reflects upon learners' historical or classroom context.

2.2.2 *Theory Theory*

The conceptions here seem to be treated as monolithic and not strongly context-specific, with a certain direction of travel[47] seemingly built in. This is sometimes referred to as *the theory theory*; a detailed example of which, in the field of physics, can be seen in the "impetus theory"[48]. This again references historical developments and the persistent nature of the theories, linking it closely to the structure of formal knowledge.

[46] Posner et al. [1982, p. 223]
[47] From non-scientific learner conceptions to normative, scientific conceptions.
[48] McCloskey [1983]

In "The Origin of Concepts"[49], Carey argues that (even) infants innately possess concept-like internal representations and mechanisms, that allow them to identify these from perceptual inputs. This is called *core cognition* and is used for evolutionarily important survival tasks. *Innately* is taken to mean without having to learn any of those aspects and this idea is pushed beyond the field of *core cognition*, to representations not perceptual in nature, such as something having a *cause*, explicitly defined as non-domain-specific. Interesting for this work is, how Carey interprets the conceptual change between two qualitatively-different representational systems *CS1* (an initial system) and *CS2* (a new system). The ideas within *CS2* cannot be expressed in terms of ideas from *CS1*, and for this reason there is a "discontinuity" that represents a true cognitive change. Carey cites the consistency of answers across multiple stimuli from learners with either of the representational systems, underlying the fact they are "theory-like". The ideas were developed by Carey that instead of a Gestalt-like switch, theory change takes place through a process known as *Quinian Bootstrapping*. To begin, a set of mental, explicit, "placeholder" symbols are constructed, partially interpreted from previous concepts. It is important to show that this is necessarily partial, as the learners do not yet have the means to express the new system. Then, a series of processes such as "analogy construction and monitoring, limiting case analyses, thought experiments and inductive inference"[50] are used to build out the definitions and define the relationships between the once placeholder concepts. Although this account provides a nice mechanism for cognitive change to occur, the lack of evidence for underlying theories being applied in the context of pre-(or even post-instruction) physics learners, as will be evidenced in Section 3.1.

2.2.3 *Framework Theory*

Vosniadou [2012] divides learners' *preconceptions* and *misconceptions* clearly. For her, learners' *preconceptions* are present pre-instruction and

[49] Carey [2009] in Carey [2011]
[50] Carey [2011, p. 120]

form a "coherent, although relatively narrow, explanatory *framework theory*"[51], where the "term theory is used loosely to denote a network of interrelated beliefs that can be used to provide explanations and form predictions and not a fully developed scientific theory". The contrast here with a scientific theory comes in that learners are not "metaconceptually aware of their beliefs and they do not understand they represent hypotheses to be falsified." Another way in which *preconceptions* differ from scientific theories, are in their ontology[52] and epistemology[53]. Physical objects/ideas must be reassigned slowly and gradually to different ontological categories, i.e. "electricity" from a manner of "energy source" to a domain of physics. These recategorisations, if successful, come with "epistemological sophistications" to interweave perceptual, everyday knowledge with a new conceptual model, reconciling the both. *Misconceptions*, on the other hand, are what may occur after instruction, when learners extend their *preconceptions* with material presented to them. This results in an internally inconstant so called *synthetic model*[54], in other words, not true *conceptual change*. This theory, although related to the previous "Theory-Theory" style, gives more flexibility. This results in a perspective that, although more inline with what is seen from learners, only adds another level of abstraction in accessing some underlying "theory", rather than attempting to describe spontaneous interpretation and problem solving more generally.

2.2.4 Ontological View

Chi [1992] places the core of cognitive change on meaning change. *Ontological Categories* are arranged in a tree-like structure, getting more specific at each level. For example, a sample ontological category for a bee might be "Matter $\rightarrow$ Natural Kind $\rightarrow$ Living $\rightarrow$ Animal". The bee has certain *ontological attributes*, like mass and colour. It would be wrong to say that you had a bee with a mass of 1kg or a pink bee, as they misdescribe the category. Another kind of error is a

[51] Vosniadou [2012, p. 122]
[52] Nature of being
[53] Nature of knowing
[54] Vosniadou et al. [2008, p. 28]

category error, assigning an *ontological attribute* that an object cannot have. This would be like saying "the bee is an hour long", as the bee does not have the "length of time" attribute - as an event, for example the "bee's lifespan", does. Of interest to us, Chi [1992] lists "electrical circuits" under "Events → Constraint based → Artificially Constructed"[55] and as we will see from Section 2.3, learners tend to see "electricity", before introductory teaching, as a kind of "material substance"[56] or "quasi-material"[57], thus requiring an ontological shift. A category error can be seen here in the statement "electricity/current flows" rather than "charge flows". It shows an incorrect or at least a too broad assignment of "electricity/current" implying that they are a material that can flow, rather a branch of science and the rate of flow of charge respectively. This category error, between the categories of "matter" and "process" in particular, is investigated by Chi et al. [1994a], where physics experts used predicates associated with processes much more, and with materials much less, than novices when explaining physics problems. Lee and Law [2001], assessing the same predicates, evidence that higher process predicate use is associated with higher physics test scores on the topic of electricity.

Chi makes some distinctions of non-radical and radical conceptual change. For radical conceptual change to occur, learners must[58]:

1. Learn the new ontological category's properties via acquisition processes;
2. Learn the meaning of individual concepts within this ontological category via acquisition processes;
3. Reassign a concept to this new ontological category:
   (a) actively abandon the concept's original meaning and replace it with the new meaning;
   (b) allow both meanings to coexist and access both meaning depending on context;
   (c) replace automatically via coherence and strength of new meaning.

[55] Chi [1992, p. 131]
[56] Chi [1992, p. 136]
[57] von Rhöneck [1981]
[58] Chi [1992, p. 144]

There is a (perhaps incongruent with constructivism) reliance on blank-slate style learning in the first two points here; there is no accounting for learning to interact with already known material. Apart from in the third point, which occurs when the new ontological structure is already in place.

Examples of processes from non-radical conceptual change are:
1. Revision of Part-Whole Relations
2. Formation of New Superordinate or Subordinate Categories
3. Reclassification of Existing Categories
4. Spreading Associations in Insight Problems
5. Direct Reassignment within Ontological Categories

If we are able to map a learners' ontological structure, or infer which ones might be common from the literature, we can see whether any of these operations listed would contribute to producing the normative ontology. For example the division of the categories of "current" and "voltage" when the two are merged in the case identified by Maichle [1981].

Chi eschews the debate as to whether learners' prior conceptions are theory-like. Defining "theorylike" to refer to a psychological coherence rather than a strict scientific definition, but ultimately calls the debate a "digression that has been misleading for the research agenda"[59], a statement with which I agree, to a large extent, as outlined in the discussion of impact on practice to come in Section 2.2.6.

The structures offered here can provide a way to think through what content is necessary to achieve learning goals, and the steps needed to attain it based on learners' prior knowledge. The strictly formalised and constrained structure of the theory, however, seems to under emphasise the flexibility and context dependence of learners' reasoning and knowledge[60] and, for this, we turn to our next and final theory.

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59 Chi [1992, p. 161]
60 diSessa [2017]

2.2.5 *Knowledge Analysis and Knowledge in Pieces*

DiSessa's idea of how systems of knowledge hang together is called *knowledge in pieces*[61], situated more widely in the study of *Knowledge Analysis*[62]. He considers learners' ideas not as monolithic, instead they are thought to consist of a large number of knowledge[63] elements. This knowledge may be inarticulate, contradictory and, crucially, highly dependant on the context in which they are applied. These properties make measuring and deciphering prior knowledge difficult and imply that even in domains that are highly abstract and removed from every day situations, ways of thinking are informed by learners' prior experiences and their invocations of *phenomenological primitives*, discussed later. It is precisely this issue of *contextuality* that is lacking in conventional conceptual change theories.

Knowledge Analysis research practice, as defined by diSessa et al. [2015], has six principles (positive integers) and three counter-principles (negative integers)[64]:

1. Knowledge is constituted in mental representations. With this diSessa states the knowledge and cognition focus of the research, aiming to produce complete and precise descriptions of the learners' understanding.

2. Knowledge can be non-propositional and encoded in various modes. Non-propositionality can be thought of as tacit or non-articulable knowledge. Encodings, in this sense, are types of (psychological) representations, and may be attained from the senses rather than the more "formal" *semantic representation*, integrating ideas and concepts.

3. Studying the mental representations of individuals requires highly nuanced accounts of content. Here, the speci-

[61] diSessa [1988]
[62] diSessa et al. [2015]
[63] Referred to throughout in diSessa et al. [2015] as knowledge* (knowledge star), to differentiate their ideas from other definitions of knowledge, dropped here for convenience.
[64] Each (counter-)principle is listed verbatim in print script from page 36-39 of diSessa et al. [2015], but a conciser explanation is then given than in the source.

ficity of thinking to the learning content is stressed, as well as, the individual level at which the thinking is done on, rejecting the formulation of sweeping generalisations. This detail orientation, content and individual level of specificity are visible in the detailed and careful discussions of interviews shown in diSessa et al. [2004]. However, from these detailed accounts, recurring features can be identified for attention in the development of curricula, i.e. we do not remain on a purely individualistic level.

4. Intuitive knowledge is an important target of study and forms of naïve knowledge are diverse, rich and generative. The meaning of this principle seems straightforward, but diSessa defines "rich" to mean the versatility of learners' conceptions and uses "generative" in the sense of learners' adaptability and the fertility of these conceptions for producing deeper understanding, even from easily overlooked features of prior thinking.

5. Studying knowledge requires full accountability to data records that capture thinking and learning processes. Here diSessa expresses the data-driven and real-time nature of *Knowledge Analysis*, rather than examining "snapshots" or "factors" related to learning and its improvement. His concern here is establishing a scientific account of the thinking and learning process.

6. Intellectual performance is highly contextual. The last principle asserts *Knowledge analysis*' commitment to explaining *contextuality*, emphasising reactivity of thought, the local and long-term history of the learner and the learning situation.

-1. Rejecting the "subset" model. diSessa hereby rejects that there are things that learners should learn including a sub-set of things they already know. Rather than seeing the learners' ideas as a *subset* of the experts', the arrow of movement is placed from learner to expert, looking at transforming learners' conceptions.

-2. Scepticism towards common-sense knowledge terms. The usefulness of the terms "concept, belief and theory" are called into question and there is a call for a high level description of models of knowledge that are "more specific and durable".
-3. Scepticism toward a-priori "modelling languages". In this final point, the need to avoid ease of description, for a level of direct empirical accountability, is established, in order to have a description that is "refined, complete and explicit".

The full impact of thinking this way will be explored in the next section, but, in brief, to contrast with conceptual change theories, knowledge must not be entirely dismantled and then rebuilt or radically changed. Instead, it is highly contextual, so continual, gradual improvement in recognising situations and applying helpful (perhaps already present) ideas are emphasised. In order to better operationalise these *Knowledge Analysis* principles, we look at two key ideas from *Knowledge in Pieces*: *phenomenological primitives* and their counter point in *coordination classes*.

Phenomenological primitives (p-prims) are a particular type of knowledge element that account for a system's "sense of mechanism". The function of a "sense of mechanism" is to account for whether a learner interprets a system as surprising or natural.[65] diSessa [2018, p. 69 - 70] gives some examples: "increased effort begets greater results; the world is full of competing influences for which the greater "gets its way,"[...]; the shape of a situation determines the shape of action within it". These simple[66] ideas are invoked without explanation behind them[67], mostly directly from the phenomena that they relate to. Invoked as a whole, they are different from a multifaceted and universal scientific theory, or from a *framework* style *preconception*, in which it is necessary (or at least possible) to reason with coordinated knowledge structures over a period of time. To account for the *contextuality* of the use, there are two parameters responsible for activating and deactivating *phenomenological*

[65] diSessa [2022, p. 47]
[66] Primitive in the first sense, as uncomplicated.
[67] Primitive in the second sense, as indivisible and elemental.

primitives. The first of these, *cuing priority*, is defined as to what extent the activation of an idea is triggered by those that have been previously activated. Whereas, *reliability priority* indicates whether a given idea will remain (reliably) activated after its initial triggering.[68] This description of *phenomenological primitives* is a "humble theory" in the sense that the authors expect them to be extended and revised, but, nonetheless, should provide helpful insights[69]. One such extension that will be useful is that of *explanatory primitives*[70], which extends the idea of *phenomenological primitives* to go beyond the "phenomenological" aspect to include those ideas with, for example, linguistic origins/connections. To reiterate principle 4, these pieces of prior knowledge are seen as something to be harnessed, rather than overcome, in contrast to previous theories discussed.

On the other hand, *coordination classes*, are intended to model well established concepts in learners approaching or attaining expertise in a given domain. Unlike the fragmentary and elemental p-prim, a *coordination class* is an integrated system with sub-structure and elements with internal cohesion. These elements are "essential properties", for example, these might include, for the *coordination class* "force", the elements "magnitude" and "direction". Having a developed understanding of such a concept involves being able to identify these elements in many situations. Thus, the *coordination class system* consists, firstly, of all possible relevant observations (*extractions*) and the network of all possible inferences between them (the *causal/inferential net*).[71] *Contextuality* is accounted for here in several forms[72]. For example, *span* refers to the learner being able to use the *coordination classes* across a range of situations and *alignment*, in which extractions from different situations are determined by the same information, giving a description of the use of *coordination classes* across different contexts.

[68] diSessa [1993]
[69] Cobb and diSessa [2004]
[70] Kapon and diSessa [2012]
[71] diSessa [2022]
[72] diSessa and Wagner [2006, p. 131]

2.2.6 *How Theory Informs Practice*

How learners' ideas are constructed in one way or another and, how the processes between individual and environment are defined and mediated, may define our view of the learner in our classroom. However, the important thing for the learning sciences, as opposed to developmental psychology, is to put these principles into practice. Much as an engineer has to employ physical principles to build a bridge, learning scientists use psychological principles to inform classroom practice. It is uncontroversial to say that we have moved beyond a purely nature or purely nurture model of development, leading up to ever more complex and mediated models in order to try and keep pace with modern biology. As these ideas were implemented there were large changes to classroom practice in the previous 100 years.

However, due partly to the myriad of influencing factors and difficulties linking different pedagogical practices directly to one particular psychological theory, it is challenging to justify completely relying on a single theoretical perspective to underlie your classroom practice. It a demanding methodological task to design experiments that show differences between differing approaches[73]. It is hard to say whether a Conceptual Change Instructional method relies on the fact that the intervention is done in a way that assumes that the learners have a "Theory Theory" preconception or, one rooted in "Knowledge in Pieces", or even if they just react "as-if"[74] they were thinking with a given conception. For example, when we show our learners an experiment with a surprising outcome, are we seeking to engender cognitive conflict or are we weakening the unhelpful and strengthening the helpful connective structures in an inferential net? Did our learners have a *framework-style preconception* or were a series of different *p-prims* being triggered dependent on their *priorities*? Are there any significant differences between them? What has been shown, is that cognitive conflict teaching methods can be counterproductive for struggling learners; they may "develop negative

[73] Sameroff and Mackenzie [2003]
[74] Schecker et al. [2018]

self-images, negative attitudes toward school and school tasks and high levels of anxiety"[75]. Consequently, this method seems inappropriate to address the needs of an entire class of learners at comprehensive schools.

diSessa [2014b] states that there "are no widely accepted, well-articulated, and tested theories of conceptual change". Unlike the engineers that can apply Newtonian mechanics reliably, classroom practitioners do not have that authoritative source. What these ways of thinking can provide us with is scaffolding to look at our materials and practice and make claims such as "by integrating a given technique, in a given setting for given learners, teaching a given topic, improved learning outcomes according to a given test were measured". This, in turn, provides a small piece of evidence with which an underlying theory may be evaluated.

All that said, in this project I take a *Knowledge in Pieces* informed stance, throughout the process. Although not every principle of *Knowledge Analysis* is fully embraced and practised, results are reflected upon using the ideas presented in the discipline. The fact that learners can call back to incommensurate ways of thinking or even use them situationally, makes it difficult to argue from a *Theory-* or *Framework-Theory* perspective. It is also the fact that if part of the construction of the new system uses analogy, then, it may be the case that, although the original understanding may be incommensurate, there maybe a suitable "source domain" with which it is not. This is addressed in relation to the materials used in this study in Section 4.3.3. It is, as we will discuss later in this chapter, difficult to construct questions that reliably test the same concept, especially before instruction, undercutting the coherence of a theory-like mental representation at that time. The fact that *knowledge in pieces* views can account for both coherence and context specificity, might be its strongest aspect (cf. Özdemir and Clark [2007]) and make the strongest refutation of a *Theory-Theory* like approach. The

[75] Dreyfus et al. [1990, p. 565]

ontological view, although not without its helpful tools for identifying particular issues, prescribes learning through acquisition, reminiscent of a "blank-slate" view of learning when engendering cognitive change. A very flexible reading of this could be that other knowledge structures could be taken as the basis and mapped into new ontologies. The fact that multiple times it has been made clear by Chi and collaborators that old ontologies are seen as more of a hindrance[76] and that reasoning with out-of-domain knowledge would constitute a different ontology, make such a charitable reading more difficult. All this makes it difficult to positively frame learners' prior knowledge, from which we aim to draw, using *analogical reasoning*, what diSessa might call "out of the shadows" learning[77][78]. In particular the scheme of work that was developed by Burde [2018] and is redeveloped here in Chapter 4, is explicitly rooted in a *Knowledge in Pieces* epistemology: we aim to implement "good instructional design, [in which] p-prims can be enlisted - rather than rejected - into excellent learning trajectories"[79].

2.3 *A Summary of Alternative Conceptions on the Subject of Circuit Electricity*

Regardless of the specific learning theory in use, one thing is clear, there are physical models of interpreting phenomena, which would be helpful to learners when trying to understand and predict the world around them. Pertinently, there are other (or alternative) conceptions, which may be of help when encountering certain phenomena in everyday life, but are of limited viability and usefulness in the science classroom. There are multiple names for these *alternative conceptions*: misconceptions, student conceptions, preconceptions and alternative frameworks, to name a few, each of which has a subtly different ideological or theoretical insinuation, discussed in previous sections. I choose to use *alternative conceptions* here as these ideas are: not always wrong in

[76] Chi [1992], Chi and Slotta [1993], Slotta and Chi [2006] in diSessa [2017]
[77] diSessa [2017], Burde and Wilhelm [2020]
[78] For a thorough comparison of the theoretical models presented here, as well as a strong refutation of theory-theory and ontological views, see diSessa [2017].
[79] diSessa [2022, p. 123]

every circumstance, not exclusively held by students or learners, persist after instruction[80] and are not necessarily seen as pre-existing thought patterns transferable by learners between contexts and may be spontaneously generated. As discussed in section 2.1.6 even physical models have their boundaries and limits, as (in counterpart) many *alternative conceptions* have situations in learners' prior experiences where they are applicable, otherwise they might not be quite as compelling.

These alternative conceptions have long since been of interest to educational researchers, as teachers try in various ways to usher learners towards correct scientific understanding and away from these common erroneous ways of thinking. Here, I will summarise and build upon the works of Wilhelm and Hopf [2018] and Driver et al. [2014] as well as the bibliography from Duit [2009].

2.3.1 The Physical Model for Lower Secondary

Before we begin discussing *alternative conceptions*, I wish briefly to show what they are alternative to. In this section I present a simplified scientific concept, for teaching in lower secondary. There is *didactic idealisation* within this description, in that I ignore electronic band structure and electron scattering. In this description wires and voltage sources are treated as being resistance free.

Charge is a property of materials. Materials can be positively or negatively charged. Atoms are made of positively charged *cores* and negatively charged *electrons*. In *insulators* these electrons cannot move from their cores, but in *conductors* it is possible for them to move. In order for them to move there needs to be a *potential difference* and a pathway to a lower potential. A battery or other *voltage source* provides a potential difference. A *closed circuit* provides a pathway. A flow of charges is called a *current*. Certain components are harder for current to flow through; the harder a material is to flow through, the higher its *resistance*.

[80] They may even be induced by instruction!

2.3.2 *The Cluster Concept Electricity*†

Alternative conceptions are not to be thought of as having well defined objects with well defined interrelations as a scientific theory does. The division between any of the following ideas: "electricity", "current", "charge", "voltage", "power" and "energy", may not be clear to a learner[81]. So many of these conceptions are general ideas that learners will seemingly transfer between these different physical quantities, so I will use electricity†[82], when referring to this nebulous concept. Such a collection of related and undifferentiated ideas can be described as a "Cluster Concept"[83]. The fact that a given *alternative conception* can be assigned to a range of physical properties can be seen as a transferral of ideas from a "deep structure" onto a current situation[84], for examples see Section 2.3.6, commensurate with the idea of *knowledge in pieces*.

The German everyday word for electricity† is "Strom", the word for current[85], and it is used in the same way as power in English in the phrase "Power Consumption" → "Stromverbrauch", so many of these misconceptions in the German literature are seen to have to do with current. This culminates in an "dominating concept"[86] of Current/Electricity† that dominates German learners' other conceptual understandings[87]. In English speaking learners, Shipstone [1985, p.35] makes explicit the lack of coherence in the words children use when talking about electricity† and interviews show the use of "it", "electricity" or, even vaguer, "something", to refer to electrical concepts[88]. This also seems to be the case for French speaking learners[89] for "électricité". Electricity† is therefore used where any of the learners refer vaguely to an undifferentiated concept in their respective languages.

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[81] Shipstone [1984], Psillos et al. [1988], von Rhöneck [1981]
[82] This is typeset as "electricity dagger", feel free to read it as just "electricity", but the "dagger" is used to make us mindful of the change in meaning from standard use.
[83] German original: "Clusterbegriff", cf. Wilhelm [2005], Schecker [1985].
[84] Niedderer et al. [1992]
[85] Although "Stromstärke" would be more correct, it is very commonly shortened.
[86] German original: vorherrschender Begriff
[87] von Rhöneck [1986a, p. 87]
[88] Osborne and Freyberg [1985], Cohen et al. [1983]
[89] Ben Hamida [1980] in Tiberghien [1984]

2.3.3 *Misconceptions Relating to Current and possibly to wider Electricity*†

Electricity† *"use"* is a widespread and resilient conception that comes in multiple forms and is shown in various ways. It is often divided into two key ideas a learner can hold regarding current: a complete usage of current and a partial usage of the current in a load. These ideas can present themselves when learners are given the task "make this lightbulb glow" or, alternatively, when asked "in which of these arrangements does the lightbulb glow?". These conceptions have been referred to as "conceptions in introductory lessons"[90], however, even advanced learners can show these conceptions after secondary school instruction[91][92]. Even when learners have internalised the fact or piece of declarative knowledge that "a circuit needs to be closed to work", they have different explanatory models for why this might be. There is an overlap here with the idea of *electricity as a fuel* or even as an industrial commodity[93], a kind of quasi-material[94] within the circuit, to be used up in different ways, as displayed in Figure 2.3.

Figure 2.3A shows a simple unipolar model, where the electricity† is transported to the lightbulb along the single wire and used up. Even if learners recognise the need for a second wire or a closed circuit, it is described as not having an active role, perhaps as a "safety wire"[95]. In the model shown in Figure 2.3B both wires carry electricity from the battery to the bulb. Existence of a second wire may be justified with the idea that the second wire is there "to bring more (or enough) electricity"[96] or that there are "two electricities a plus and a minus"[97]. The "partial usage" model is shown in 2.3C, which gains in popularity as learners age (and perhaps see the need for a closed circuit), only to be

90 From the German "Vorstellungen im Anfangsunterricht" from Wilhelm and Hopf [2018]
91 Fredette and Lochhead [1980]
92 Andersson and Kärrqvist [1979] in Driver et al. [1985]
93 Muckenfuß [1980, p. 33]
94 von Rhöneck [1981]
95 Driver et al. [2014]
96 Johsua and Dupin [1987, p. 124]
97 Dupin and Johsua [1985, p. 334]

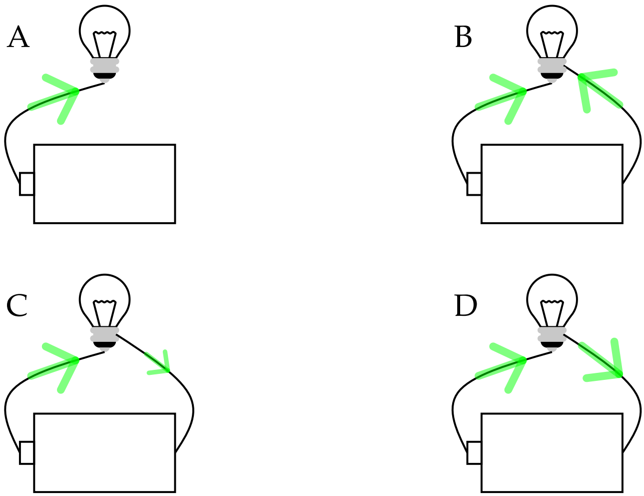

Figure 2.3: Four Models of Current beginning with a simple unipolar model (A), a "Clashing Current" model with two wires (B), a "partial usage" model (C) and finally the "scientific model" (D) as first measured in Osborne and Freyberg [1985]. Green arrows represent current: the direction and the size.

overtaken at sixth-form level[98] by a physical model of current[99], shown in 2.3D. These models, first established by Osborne and Freyberg [1985] in New Zealand have since been found many times over in other countries: the UK (England, Wales and Northern Ireland)[100], Australia[101], Greece[102], Sweden[103], and France[104]. An interesting illustration of the fragility of such *alternative conceptions* is that if the students are given a lantern- or 3R12-battery[105], instead of a round battery, most can con-

[98] British Advanced school leavers opting for physics and studying it from the ages of sixteen to eighteen.
[99] Shipstone [1984]
[100] Shipstone [1985], Gott [1984]
[101] Butts [1985]
[102] Psillos et al. [1987]
[103] Andersson [1984]
[104] Dupin and Johsua [1985]
[105] Called a "flat battery" in Tiberghien [1984] presumably a "Flachbatterie" rather than a spent battery as in English.

nect it correctly[106]. These are 4.5 V batteries with two elongated metal plates as terminals, common in mainland European science classrooms, comparable with the use of 9 V batteries in U.K. science classrooms, before battery holders became common. Possibly, as the battery has two clearly visible terminals, the unipolar model is not even triggered.

As mentioned, if learners see electricity as something that gets "used up", it may follow to regard current as a fuel[107] or as energy[108][109], with batteries as a store of electricity†[110]. English speaking learners, when asked about bulbs with power ratings, said "something", perhaps power or electricity†, is used up in proportion with the power rating[111]. Energy, although not physically getting "used up", is converted, which learners also regard as being "used up". This is a common conception, especially in German, where a circuit component is often referred to as a "Verbraucher", roughly translated as "user". Usage conceptions are even present when learners are asked about voltage and not in the close to physical way that one may describe Kirchhoff's voltage law[112]. This kind of *usage* may be seen as being dependent on the value of resistance, a larger resistance (or perhaps resistor) using more electricity†. This is shown in implicit thinking alongside *sequential reasoning*, when learners analyse a series circuit with changing or variable resistors[113] and I will call it *resistance proportional to usage*, following Burde [2018, p. 48].

In parallel circuits, as discussed in von Rhöneck [1986b, p. 13], *increasing current with increasing resistance* must be interpreted as a different idea to that previously, as the current *use* and *sequential reasoning* cannot be assumed in this case. The idea, that more current flows through a larger resistance is named the *inverse resistance* conception by Burde [2018, p. 49].

[106] Delacote and Tiberghien [1976] in Tiberghien [1984]
[107] von Rhöneck [1986b]
[108] Osborne and Freyberg [1985]
[109] von Rhöneck [1981] in Tiberghien [1984]
[110] Maichle [1981] in Tiberghien [1984]
[111] Cohen et al. [1983]
[112] von Rhöneck [1980, p. 25]
[113] Shipstone [1984, 1985]

Heller and Finley [1992] saw in an interview with a learner the idea that "more current is used in travel[l]ing the extra distance to the bulbs"[114], this leaves it slightly up to interpretation as to whether this is because the learner thinks that the wires "use up" the current sequentially to the bulbs or whether the distance is the deciding factor, compare Johsua and Dupin [1987, p. 123], dubbed the "current wearing out" conception. The pure distance conception, as in the interpretation by Morris [2018, p. 8] will be referred to as the *current-distance relation*.

"Electricity† is supplied" or in German "Strom wird geliefert"[115] is evidenced through a forum post in Wilhelm and Hopf [2018] and this phrase and related ones were common in German language text books according to Stork and Wiesner [1981][p. 219]. I will call this idea *current is delivered* to contrast it with the everyday phrase. The learners in Stork and Wiesner [1981], however seem to attribute agency to the load on the circuit: "pick up/grab something"[116]. This idea is similar to the physical idea of "current draw" in English, but can be harmful if a causative characteristic is given to the pulling or "sucking" of current from the battery. I will call this idea *current is taken* to contrast it with the idea of *current draw*. Related to this is the idea that current is the same regardless of the resistance or that the battery provides or delivers a constant current[117], rather than a constant potential difference, i.e. *battery gives constant current*.

Electricity† can also be *shared*. Shipstone [1985, p. 37] describes a reasoning based on identical components and reasoned at the level of the whole circuit, but current is not regarded as being conserved. This is perhaps unsurprising as sharing is a key societal theme prevalent cross culturally and central to most children's socialisation.

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114 Heller and Finley [1992, p. 272]

115 The German word "geliefert" is more closely translated as "delivered", but the full phrase is closer to the English everyday equivalent given here. However, "delivered" implies a more active role for the voltage supply in this instance

116 German original: "Das Birnchen hat sich [...] was geholt." in Stork and Wiesner [1981] [p. 227]

117 Cohen et al. [1983], McDermott and Shaffer [1992], Licht and Thijs [1990], Dupin and Johsua [1987]

Although not quite as omnipresent as in German, English speaking learners too tend to use current as their primary concept to reason through a problem more often than voltage and sometimes inappropriately[118]. This may overlap with other ideas, notably *sequential reasoning* and *local argumentation*, but will be categorised separately as *arguing from current*.

To summarise, there are a few key concepts which can be invoked when learners reflect on electricity† or later current, both of which can be the physical idea of a flow of charge or a kind of quasi-material used in making electric circuits function. Learners associate this with certain actions it can do, the primary of which is *use*, i.e. something getting used up while moving around or within the circuit. Whether the electricity is used fully or partially and under what circumstances, i.e. whether a complete circuit is necessary or how it gets used, either in the wires or just the components, makes this idea flexible and possibly therefore resilient. *Sharing* is another keyword that can be used together or apart from the use term. The next is *deliver*, both may be accompanied by giving the current/charge agency and resulting in placing current at the core of explanations of the nature of circuits. The latter two have a tendency to personify components or the charges themselves.

2.3.4 *Misconceptions Relating to Voltage*

Voltage has a comparative nature, making it essential to tell the difference between *potential* and *potential difference*, something that learners find difficult. This shows itself, for example, in learners viewing components at a higher potential being a defining factor, rather than the potential difference over them[119]. Some learners may remember the need for connecting to the plus and minus poles of a battery when measuring its potential difference, but not apply this "pole rule" consistently over other components or appreciate why[120].

[118] Cohen et al. [1983, p. 409]
[119] McDermott and Shaffer [1992]
[120] von Rhöneck [1980, p. 20]

Some learners (both pre- and post-instruction, years eight and nine[121] in German technical school[122]) see no connection between voltage and current in their role in a circuit[123]. On the opposite extreme, for some learners voltage and current are so closely linked they do not differentiate them at all[124], perhaps a way in which learners' *cluster concept* is expressed. This carries through to post-instruction in one-in-five learners as is shown in the fourth and final statement in Table 2.1.

Jung [1985] measured that 19% and 40% of German Year eights ($n = 70$) and Year tens ($n = 73$)[125] view voltage as a property. However, cautions the reader to not put too much store by this as according to unpublished work by Ulla Maichle, even few adults have switched from verb usage from "is" to "have" when discussing properties[126]. Maichle [1980] defines a "TRANSFER-Schema"[127] to reflect learners' understanding pre-instruction, within this voltage is assigned as a property of current/electricity†.

Statement	Agree	Disagree
Every electricity†/Current has a Voltage *Jeder elektrische Strom hat eine Spannung*	90%	(10%)
Electricity consists of a Current and a Voltage *Der elektrische Strom besteht aus Stromstärke und Spannung*	65%	(35%)
A Voltage can also exist without a Current *Eine elektrische Spannung kann auch ohne elektrischen Strom vorkommen*	(30%)	70%
You can call electricity†/Current a Voltage *Den elektrischen Strom kann man auch Spannung nennen*	20%	(80%)

Table 2.1: True or False answers to statements about electrical circuits post instruction from Maichle [1980][p. 10]. The italicised German language versions are the original. Percentages in brackets are calculated from learners answering the opposite.

121 Aged 13-14 Years and 15-16 Years, respectively.
122 Realschule
123 von Rhöneck [1980]
124 von Rhöneck [1980], Maichle [1981]
125 Aged 13-14 Years and 15-16 Years, respectively.
126 Jung [1985, p. 201]
127 German original: "Verteilen-Schema", translated in Engelhardt [1997] as "TRANSFER-Schema".

Looking at the results from Table 2.1, this way of thinking seems persistent after instruction. However, if we exercise the same caution Jung [1985] advises about learners discussing properties, although the first statement is false in the sense that a current does not "have a voltage", it does, for example, "have a voltage" as its cause. The nuances of such semantic differences make answers to such a question difficult to interpret. However, with the pre-instruction interviews, the known resilience of pre-instruction thinking as additional evidence and such a high proportion agreeing with the statement, it seems the most likely outcome that at least the *voltage as property of current* part of the TRANSFER-Schema is also present in some learners after instruction.

The second statement in this table is more explicit in referring to the property nature. Also, calling attention to the fact electricity and current are not the same thing, by explicitly using both nouns. However, from my (albeit unsystematic) teaching experience with undergraduates, learners misuse the verbal phrase *besteht aus*[128], when they have a developing idea of the system and wish to link concepts together. I also find it less easy to say this question has a definitive answer. The web of ideas in the domain of electricity does *consist of*[129] the concepts current and voltage, but they are not "ingredients" of electricity in the same way a cake consists of flour, butter and sugar. For this reason, this question seems to have a too large a room for interpretation to make the answer reliable and no additional interview evidence is provided.

As in the first statement, the third statement lacks a clear division between current and electricity[†], which may make interpretation difficult for the learners. The clearest interpretation would be that learners see voltage as only possible when current is present. This idea is dubbed *No voltage in absence of current*[130], which some students reason using, and overgeneralising, Ohm's Law, $V = IR$[131]. The fourth statement is discussed above.

[128] German for *consists of*.
[129] Contains as essential and core components.
[130] von Rhöneck [1981, 1984]
[131] Johsua [1982] in Tiberghien [1984]

Although a resistance is a necessary condition for establishing a potential difference, some learners struggle to differentiate the properties, using concepts that indicate one to refer to another, for example talking of a "resistance drop" or a "2 Volt Resistor"[132]. Learners also seem to struggle to reason how the constance of potential difference from a voltage source relates to a varying resistance[133]. Although it is unclear from the examples given where the origin of this difficulty is, i.e. whether it is the overgeneralisation of a constancy rule or whether the idealisations of Ohmic resistors, when compared to the resistance characteristics of a light bulb, are not clearly compartmentalised.

Voltage seems to be able to illicit a wide range of misconceptions from our learners in a much more varied and complex way than current seems to. This be because of its more abstract, comparative nature and the fact it is often introduced after and in relation to current and resistance. This will be reflected in the teaching material developed in later chapters.

2.3.5 Other Difficulties

The fact that resistance has not been afforded its own subsection here may be quite telling, as it is often seen only in its relation to the other key physical quantities. Muckenfuß [1980, p. 35] notes the lack of conceptions of resistance related to science, only those related to social issues i.e. "non-violent resistance", "resistance to progress/reform" and "resistance from parents". These ideas can prove helpful, as they do not overlay with the dominant *electricity*† *use* key idea, where a resistor may be seen to consume rather than hinder[134]. All the above social ideas map onto the idea of a hindrance nicely. Other difficulties regarding resistance are its relation to length and cross-sectional areas of the material, whereby the former seems relatively intuitive[135].

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132 Riley et al. [1981] in Tiberghien [1984]
133 Johsua [1982] in Tiberghien [1984]
134 This extension of the *usage* key idea can be seen for example in von Rhöneck [1984, p. 5].
135 Johnstone and Mughol [1978, p. 49]

The lack of sufficient separation between idea of the physical quantity "charge" and the physical object "charges" (or more clearly "charge carriers" or "charged particles"), provides a barrier to understanding.[136] Muckenfuß [1980, p. 36-7] also discusses possible difficulties related to the use of "Ladung" (charge) in everyday language, this also goes for the use of "charge" in English. For example, "(re-)charge a battery" or "out of charge" reinforces a *useage conception*, in these instances, of charge.

The following two difficulties refer to learners' difficulty with the nature of the electric circuit as a system. Sequential reasoning[137] indicates the idea that learners argue by following the current around the circuit, instead of regarding the circuit as a whole system. What happens "first" to the current is seen as important and influencing the rest of the circuit after it. For example, combining this and the *current use* idea, for two bulbs in series, the first to get the current would be brighter than the second, that receives the "left over" electricity. This way of thinking seems present across ages[138]. The prevalence of this *alternative conception* seems to peak after initial instruction, but one should exercise caution when interpreting these results as the lowering is concurrent with physics becoming an optional subject at A-level.

Local argumentation[139], again, does not regard the circuit as a system, but learners can do this in a way unrelated to the sequential nature. An example of this would be, looking at a branching circuit and, without looking at the resistances on the branches, ascribing a behaviour to the current at that point, commonly that it splits evenly among the branches. When a change is made to the circuit, learners may focus on the part that has been changed and not reason holistically[140].

[136] Johsua and Dupin [1985]
[137] Closset [1984a,b], Tiberghien [1984], Duit [1985], Shipstone [1984]
[138] Riley et al. [1981] in Urban [2017]
[139] Cohen et al. [1983], Riley et al. [1981], Closset [1984b]
[140] McDermott and Shaffer [1992, p. 1001]

To draw into sharp focus the difference between the absence of *local argumentation* and reasoning holistically, learners may only look at the components in the circuit completely ignoring the way the circuit is put together[141]. The form of the circuit is clearly essential to determine its function, but the way a circuit works is dependent on its topology and not geometry[142]. This is identified in Caillot and Chalouhi [1984], where learners are asked to identify functionally identical circuits from diagrams with different geometrical layouts. One way in which this problem with the circuits' topological nature can show itself, is in the emphasis learners put on physically superficial changes in circuit diagrams. For example, identifying resistors with parallel lines as resistors in parallel, rather than the physical property[143], which I will call the *geometrically parallel* conception. Additionally, in Niedderer [1972] learners judged a symmetrical circuit more likely to work. This may be in general related to *encoding and decoding difficulties* between the levels of circuit diagram, drawing of a circuit and real circuit. This encoding and decoding issue is often obvious only obliquely. For example, it is measured by proxy in a practical situation in Finkelstein et al. [2005] by the length of time taken for learners to build, dismantle and describe a circuit from a diagram, but is not a central focus of the investigation.

Learners in von Rhöneck [1986a] seem to have more difficulty answering questions with measuring instruments for current and voltage rather than dots on the circuit diagram asking them about the corresponding properties. This may result from asking "What does the voltmeter show?" making the comparative nature less obvious than the questions "What is the voltage over X component?" or "What is the voltage between points Y and Z?".

[141] McDermott and Shaffer [1992, p. 998]
[142] In other words, circuits with geometric layout differences (longer wires, components rotated or translated) still function in the same way.
[143] Caillot and Chalouhi [1984, p. 41]

Learners also *argue from utility*. For example, learners in Johsua [1982] referenced in van Aalst [1985, p. 124] argue against the current in a short-circuit bypassing a resistor, by stating the resistor "could not be without utility".

Quotes from interviews by van Zee et al. [1982] reported in Tiberghien [1984] illustrate two final general difficulties. Learners *personify* components, attributing human actions to them. The quotes also make explicit that this learner is *unwilling or unable to reason qualitatively* despite, or possibly even because, being well acquainted with the quantitative rules for analysing circuits, as also seen in Cohen et al. [1983].

This concludes a rather long summary of the possible *alternative conceptions*. There is an overview shown in Table 2.2.

Name	Description	Source(s)
Partial Electricity Use		Osborne and Freyberg [1985], Shipstone [1984], etc.
Total Electricity Use		Osborne and Freyberg [1985], Shipstone [1984], etc.
Electricity as Fuel		von Rhöneck [1986b]
Resistance Proportional to Electricity Use		Shipstone [1984], Shipstone [1985]
Clashing Currents	Current comes from both terminals.	Osborne and Freyberg [1985], Shipstone [1984], etc.
A Plus and a Minus Electricity	Same as above with a plus and a minus current.	Dupin and Johsua [1985]
Current-Distance	Current diminishes with distance.	Heller and Finley [1992]
Current Wearing Out		Johsua and Dupin [1987]
Current is Delivered	Current is agentic.	No academic primary source found.
Current is Taken	Component is agentic.	Stork and Wiesner [1981]
Battery Gives Constant Current		Cohen et al. [1983], McDermott and Shaffer [1992]
Electricity Sharing		Shipstone [1985]
Arguing from Current		Cohen et al. [1983]
Inverse Resistance	Higher Resistance, Higher Current.	If *use* not assumed: Shipstone [1984], Shipstone [1985]
Comparative Nature of Voltage	Potential vs Potential Difference confusion.	McDermott and Shaffer [1992]
No Relation Between Voltage and Current		von Rhöneck [1980]
Voltage is Current		Maichle [1981]
Voltage as a Property of Current		Maichle [1980]
No Voltage in the Absence of Current		von Rhöneck [1981], von Rhöneck [1984]
Undifferentiated Properties	Properties of V, I or R used to describe each other.	Riley et al. [1981] as cited in Tiberghien [1984].
Voltage Dependent on Resistance		Johsua [1982] as ref in Tiberghien [1984].
Charge Property vs Object Distinction		Johsua and Dupin [1985]
Sequential Reasoning		Closset [1984b]
Local Argumentation		Cohen et al. [1983]
Topological Nature Difficulties	Geometry taken as determining function.	Caillot and Chalouhi [1984]
Geometrically vs Physically Parallel		Caillot and Chalouhi [1984]
Problems with Measuring Apparatus		von Rhöneck [1986a]
Argumentation from Utility	Component must "work", because it is present.	Johsua [1984]
Personification		van Zee et al. [1982] as cited in Tiberghien [1984].
Rule Overgeneralisation	Learners lack sufficient *span*.	e.g. $V = IR$ in Cohen et al. [1983]
Encoding and Decoding Difficulties	Real Circuit ↔ Drawing ↔ Diagram	Measured implicitly in Finkelstein et al. [2005].
Unwillingness to Reason Quantitatively		Cohen et al. [1983]

Table 2.2: *Alternative Conceptions* and general difficulties listed in Section 2.3 with summaries and a non-exhaustive list of sources.

2.3.6 Considering Underlying Schemata

Duit et al. [1985][p. 15] consider some underlying schemata for some of these specific misconceptions to be:

- the source-consumer-schema
- the give-take-schema
- the share-schema
- the sink-schema
- causal schemata [...][144]
- misconceived 'prototypes' (in-series, in-parallel)
- the whole-part-schema
- the energy-transfer-schema
  [...]sequential reasoning

Considering these underlying schemata from a *Knowledge in Pieces* standpoint, we can see that these (with the exception of "misconceived 'prototypes'"[145]) could be seen as *p-prims* that learners call on to explain different aspects of electrical circuits. These examples also have utility, as the learners will need to use these ideas in their daily lives and can be useful to explain some of the key attributes of electrical circuits, if directed fruitfully. However, this list (and also student ideas from the literature) is very current focussed, as mentioned earlier. And so, this means necessary ideas for a strongly explanatory concept of potential are missing. These are discussed in Chapter 4.

2.3.7 Language Resulting in Alternative Conceptions

As measured in Shipstone et al. [1988] there is surprising coherence across languages and national schooling systems of the alternative conceptions present in learners' thinking. However, the language we speak has considerable influence over the way we think. This is well shown by Duit [1984b], with reference to these usages forming the basis of the pre-existing knowledge that the learners bring with them into

[144] Defined by diSessa [2014a, p. 799] as "what a learner takes as general, explanatory, and predictive about a class of phenomena".
[145] I interpret this as an emergent *coordination class* without sufficient *span*.

		Conceptual Meaning	Logical, cognitive, or denotative content.
Communicative Value	Associative Meaning	Connotative Meaning	What is communicated by virtue of what language refers to.
		Social Meaning	What is communicated of the social circumstances of language use.
		(Affective Meaning)	What is communicated of the feelings and attitudes of the speaker/writer.
		Reflected Meaning	What is communicated through association with another sense of the same expression.
		Collocative Meaning	What is communicated through association with words which tend to occur in the environment of another word.
		Thematic Meaning	What is communicated by the way in which the message is organized in terms of order and emphasis.

Table 2.3: Seven types of meaning as summarised on Leech [1981, p.23]. Affective meaning is shown in brackets here as it is both not addressed in this section and that it is not considered by Leech a type of associative meaning. All seven types of meaning are referred to as *communicative value* collectively and those referred to collectively as *associative meaning* are shown between the horizontal lines, with the aforementioned exception.

the classroom. Duit [1984b] breaks the origins of these misconceptions down into three sources: 1) notions provided by language, 2) the structure of the language and 3) the usage of physical concept names in everyday language. Taking Leech [1981]'s "seven types of meaning", we can offer these thoughts a theoretical foundation and expand on their origins.

In physics lessons we aim to guide learners to be able to use a deeper and considered *conceptual meaning* of the terminology: showing their understanding of the term and ability to express its *contrastive* and *structural* features. *Contrastive* features, as the name suggests, look at associated categories in which the word is or is not contained. For example, Leech [1981, p. 10] defines "boy [...] as + human, + male, - adult". An example from electricity might be defining resistance as '+ physical quantity + material dependent + flow restriction'; the exact categories will be dependent on the learning objectives of the teaching sequence. *Structural* features define how to use this newly learnt word: the function it serves in a sentence (what part of speech, i.e. noun or verb, it is), or the verbs or other parts of speech it may interact with. This denotative or logical content is not the extent of language, however. The *connotative meaning* of the way we speak about electricity in the everyday sense, stands in direct contrast to how we use it in physics. Additionally, whether the conceptual content that is intended by the speaker/writer is understood by the audience, will be focussed through an associative lens, i.e. what does the word mean from a speaker or listener's reference point. Duit [1984b] uses the example of "the sun rises", being a true observation going against a scientific, heliocentric view of our solar system. An example from electric circuits might be "switch the electricity on", which although perfectly acceptable in everyday speech, does not acknowledge the processes of a switch closing, creating a pathway for current, over which must be a potential difference, but instead imbues the "electricity" with a kind of "power" of its own. In fact, even experts will use these kinds of phrases in their everyday speech, fully aware of the true denotative content behind them, perhaps encoding using *social meaning* markers that they no longer in their role as scientist, commonly called *code switching* but more precisely referred to in linguistics as *register shifting*[146]. We see here the difference between the *conceptual meaning* as a kind of philosophical/logical object and the *connotative meaning* as a more psychological object.

Duit [1984b] argues that the subject-predicate-object structure leads to cause and effect thinking, structural importance related to Leech's *thematic meaning*. The tendency to use these simple structures, lead to *local argumentation* and *sequential reasoning*, suggests Duit [1984b]. As well as seeing quantities with unclear meanings as "quality of an object" as with the idea that voltage is a property of current, leading to a false schema and categorisation of contrastive or structural features.

[146] Bullock and Toribio [2009]

The final point is the borrowing or overlap between scientific vocabulary and everyday vocabulary. These misinterpretations occur as a result of *reflective* and *collocative* meanings. The word "current", for example, refers not just to the flow of electricity, but that of rivers and oceans. The word has multiple possible *conceptual meanings* that are then reflected in each other, meaning ideas about one can be transferred to the other, which can be both useful and disadvantageous in teaching about a topic, again reflective of the learning outcomes. *Collocative* meanings are transferral of meanings from words that often go together. This again can be both advantageous or disadvantageous. The phrase "electricity usage" can support a current use misconception and within an interview shown in section 3.1 a pre-instruction learner reasoned the meaning of resistance being to do with hindrance with reference to the phrase 'resisting arrest'.

Duit [1984b] belies a difficulty of translating the understanding of physical concepts across language barriers. He uses examples that are not entirely comprehensible in the translated English, as they would be if the author was writing in his native German. For example, he references the phrase "the weightlifter has force" from a German publication of his "der Gewichtheber hat Kraft"[147]. The phrase in English sounds unconvincing and is better translated with "the weightlifter has (the) strength", showing the perils of translating phrases literally and how that the words "force" and "Kraft" may carry different associations, based upon the usage of the words in their respective everyday conversations. This functions as an illustrative example to justify the validation of any instrument across languages, as will be illustrated in section 3.1.

2.4 *Measuring Alternative Conceptions and Learning Gains*

The standard graded school test is ubiquitous and familiar to everyone, however the goal of a knowledge test can be multifarious. Considering why one is using a given test, the intended audience and additional information that one can extract, allows teachers and researchers alike

[147] Duit [1984a] in Duit [1984b]

to make better use of tests than just for summative assessment[148]. Much more information can be extracted from a test than just a percentage mark.

2.4.1 *Alternative Conceptions as Distractors and Something Measurable*

Rather than simply marking a given test right or wrong (scientific or unscientific thinking), the distractors of a test can be developed and assigned to *alternative conceptions*, providing richer information. If performed as a pre-test, the researcher can learn what ideas are prevalent in the population and for a teacher this might be a useful tool to plan for addressing these ideas, allowing teachers to 'know their competition'. Additionally, richer information can provide a better insight as to the progress of learners over and above a dichotomous true or false. When comparing pre- to post-test, as learners' ideas can be organised hierarchically in closeness to the scientific conception. This can be seen, for example, in Hadenfeldt et al. [2016] on the particle theory of matter, systematising the complexity of thinking into 5 "levels of understanding" and compare progress that way. Such hierarchical levels can be conceptualised more generally as "everyday", "school informed" and "scientific" ways of thinking, where there may be multiple examples of each way of thinking, even compounding.[149] However, it is important to not consider these levels as a natural or even expected progression, as learners often "regress"[150] to previous ways of thinking, even misremembering evidence presented in order to address their "everyday" ways of thinking.[151]

[148] This is the kind of assessment that asks "What has been learnt?" at the end of a topic and refers more to an assessment paradigm rather than a given method, but is often synonymous with the graded test. For more about summative assessment's counterpart, formative assessment, see Section 4.4.2.
[149] Hericks [1993]
[150] Cosgrove and Osborne [1985]
[151] Gauld [1986]

As the conceptions often lie at an underlying explanatory level[152] these tests are often two-tiered - with a 'what' level and a 'why' level[153]. Learners may also recall a rule correctly but still have an underlying misconception - for example, know that current is the same at all points in a simple loop circuit, but say current/electricity[†] is split evenly among the components in the circuit[154]. In such cases we can measure more closely whether a deeper level cognitive change has occurred. The second tier also has a secondary effect in that it reduces the amount of false-positive diagnoses for a given alternative conception. For example, when a diagnosis is made on the basis of selecting one of five single-tier answer choices, there is a false-positive chance of 20% when a learner is picking randomly. The diagnosis made on the basis of answer combinations on a two-tiered test reduces the likelihood of the answer simply being chosen at random. For example, five answer options followed by five answer options, reduces this likelihood from 20% to 4%.

2.4.2 *Tests on the Topic of Electricity*

There are many single choice test instruments for testing understanding within the domain of physics, probably the most well known of which being the *Force Concept Inventory*[155]. This test, among others, is designed to measure whether learners have understood an underlying concept, for example, that "constant acceleration [results in] a parabolic orbit"[156] and distractors may or may not be based upon supporting research on learners' *alternative conceptions*. This review looks at tests created after 1997, for those created before that date "statistics associated with the reliability and validity [...] are almost non-existent"[157]. However, for a review of those produced before this time, there is a thorough review in Engelhardt [1997].

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[152] Items do not simply ask 'What do you think?', but set the learners a task to apply their knowledge and the conception is deduced from those answers.
[153] Burde [2018], Urban-Woldron and Hopf [2012], Ivanjek et al. [2021]
[154] Maichle [1980, p. 12]
[155] Hestenes et al. [1992]
[156] Hestenes et al. [1992, p. 1]
[157] Engelhardt [1997, p. 64]

Within the topic of electricity there are several tests in the English language[158] and beyond[159]. The tests on the topic of electricity vary in intended age and ability of learners, as well as learning outcomes tested. Questions within a test are often referred to as "items". Such tests are not often freely shared as researchers are concerned that teachers in their interventions will "teach to test", rendering the point of checking underlying understanding useless, by the repetition of rote answers[160].

Sangam and Jesiek [2010] discuss four English language concept inventories on the topic of electricity, one is intended exclusively for electrical engineering undergraduates, the Circuits Concept Inventories (CCI)[161]. This is apparent by the fact it contains networks of resistors and the inclusion of capacitors, as well as alternating currents and graphical interpretations of transient voltages unsuitable for an introduction to the topic in lower secondary. Although Sangam and Jesiek [2010] class it as a "quantitative assessment", this is only strictly the case with items 17-22, with 17 asking for an equation and 18-22 testing the ability to read specific physical quantities from a graph. Therefore, not matching what would be most commonly understood by a "quantitative assessment" of students abilities, among physicists, despite the numerical answers to many items.

Secondly, Sangam and Jesiek [2010] introduce the Electric Circuits Concept Evaluation (ECCE)[162] with 45 single-tiered, single-choice items, pitched at undergraduates in the United States of America. 4 items ask, in addition, "Briefly explain [...] how you arrived at your answer [...]" to a selection of questions. Multiple questions are asked for a given circuit. Six items have capacitors (Questions 17-20) or inductors (Questions 21-22) included in the questions and the questions 39-45

158 Sangam and Jesiek [2010], Halloun [2007]
159 Burde [2018], Urban-Woldron and Hopf [2012], Ivanjek et al. [2021]
160 A fear, I personally find unfounded, as considering the prevalence of the research-practice gap, teachers and learners seem unlikely to seek out specific tests from science education or didactic literature.
161 Kindly provided to me through personal communication with the author, Prof. David P. Rancour.
162 Sokoloff [1996]

ask about alternating current, so beyond the scope of lower secondary. This leaves 32 items that possibly have a use in lower secondary, the learning outcomes of which are summarised in Table 2.4. The questions contain up to 10 answer possibilities and references to diagrams stretch beyond a page requiring learners to keep a lot of information in their short term memory. This test, despite having some good situations for developing items for lower secondary, on the whole is not applicable.

Thirdly, the Electric Circuits Concept Evaluation (DIRECT)[163] is a 29 item, single-tiered single choice test, each with 5 answer options. In her doctoral thesis Engelhardt [1997] gives an account of how the test was developed and then re-developed, both with statistics and interviews, with specific reference to misconceptions. There are a set of objectives clearly defined (p. 72) and linked with specific items. Only three of the learning objectives (6, 7 and 9) are not applicable to the learning objectives of the cohort under investigation. Using the mapping of objectives to items on page 136, items 2, 3, 11, 12, 20 and 21 could be omitted to form the basis of a suitable test. Although the internal consistency measures are only "moderate"[164], the test fulfils a range of other quantitative tests, only narrowly failing to have a high enough discrimination index. Qualitative interviews were collected with a subsection of the questions and the results of which, when analysed, "indicated that, in general, students were interpreting the questions correctly and that the exam was eliciting their misconceptions"[165]. The high school learners completing this test were all 18 years-old, making much of the analysis and development less applicable to our target group of twelve- and thirteen-year-olds, despite having a reasonable overlap in learning objectives. For these reasons and with the aforementioned caveats, I consider this test the most appropriate English language electricity concept test, for my purposes, available at the time of writing. A version with revised wording (Ver 1.2) is available as used by Sangam and Jesiek [2012].

[163] Engelhardt and Beichner [2004]
[164] Engelhardt [1997, p. 80, p. 85]
[165] Engelhardt [1997, p. 154]

Q	Learning Objective Tested	Situation
1	Current Conservation	Simple Loop
2 3 4 5	Current in Parallel Circuits Current in Parallel Circuits Brightness-Current Relation Potential Difference in Parallel Circuits	Two bulbs in Parallel
6 7 8	Current in Series Circuits Potential Difference in Series Circuits Brightness-Current Relation	Two bulbs in Series
9 10 11 12 13 14 15 16	Current in Branching Circuits & Brightness-Current Relation Current in Branching Circuits Potential Difference in Branching Circuits Function of Switches & Analysis of Voltage and Current in Network of Resistors Identifying Resistors in Parallel Identifying Resistors in Series and Parallel	Bulbs in Mixed Circuit with Switch
17 - 20	Capacitance	
21 22	Inductance	
23 24	Identifying Resistors in Series Identifying Resistors in Parallel	Mixed Circuit with Resistors
25 26	Identifying Resistors in Series Identifying Resistors in Parallel	Series, Parallel and Short Circuits with Resistors
27 28	Current Conservation	Three identical Resistors in Series
29 30	Current Conservation	Three non-identical Resistors in Series
31 32 33 34 35 36 37 38	Current in a Network of Resistors	Three identical Resistors, two in Parallel, one in Series Three non-identical Resistors, two in Parallel, one in Series Three all different Resistors, two in Parallel, one in Series Series, Parallel and Short Circuits with Resistors
39 - 45	Alternating Current	

Table 2.4: Summary of learning objectives and contexts from the Electric Circuit Concept Evaluation developed by Sokoloff [1996].

Finally, the AC/DC Concepts Test (ACDCCT)[166] is a single-tiered, single choice, 20 item test intended for use with undergraduates. Despite reaching out to the authors, I was not able to obtain a copy for further analysis. There are, however, two considerations in Holton et al. [2008] worth developing in a further discussion on test development: *test-wiseness* and *temporality*. Learners can search the question text for information that can lead them to answer correctly despite not knowing the answer to the question. We call the ability to do this *test-wiseness*. Holton et al. [2008, p. 8] develop a list of eleven cues that are taken into account when redeveloping the test used in the intervention in Section 3.1. Learners are shown to perform significantly worse on questions that have a *temporal* nature, i.e. what happens in a circuit over time[167]. Holton et al. [2008, p. 14] also note that misconceptions are prevalent throughout the cohort and the major difference in test scores comes from knowledge of circuit invariants.

Other tests available in English and in this case French include the Inventory of Basic Concepts - Direct Circuits (IBCDC)[168]. It is a 33 item single-tiered test, testing a wide range of concepts in DC Circuits in school age and undergraduate learners and tested with a large number of participants. The test has undergone multiple iterations and redevelopments. It is successful in covering a lot of material succinctly in relatively few five option items, see Table 2.5 for an overview. The test has a focus on "real world" visualisations of circuit problems and correct connections to batteries and bulbs, which should be considered if wanting to use the test. The separation of bulb brightness and current is a nice feature, not assuming that learners see the relation. Furthermore, there are items regarding internal resistance as well as abstract "black box" problems, which may not be desirable difficulties in such a test. Furthermore, the English used is somewhat non-standard and at some points difficult to read, even for an academic native speaker. Finally, the answers to some items seem ambiguous, rest on conventions or

[166] Holton et al. [2008]
[167] Holton et al. [2008, p. 13]
[168] Halloun [2007]

differing levels of pedagogic *idealisation*[169]. For example, Item 14 has multiple possible answers (each with different caveats) and similarly Item 16 (with the "black box") has different correct answers depending on the components inside, but would not be known to a learner who has only studied DC Circuits. This may be considered to be intended, as a hierarchy of models is discussed in Halloun [2007, p. 4], although this is explicitly stated to be not the case on page 13 of the same document. In general, evaluation of learners' conceptions from the test are never explicated upon. Some items on this test would offer a good basis for further development. However, due to more promising examples covering the same ground, I do not carry out further work on this basis.

Originally in Turkish, the Simple Electric Circuits Diagnostic Test (SECDT) also has an (not verified) English language translation[170]. This test has twelve items trialled with Turkish fourteen to sixteen year-olds and each is three-tiered, the third tier of which is a binary choice: "Are you sure about your answers given to the previous two questions?", with learners being able to answer "Sure" and "Not Sure". The test would require rewriting in English. The first two items follow the typical "what", "why" pattern with an open "why" answer. A Cronbach's α of 0.69 (close to the 0.7 recommended by Nunnally and Bernstein [1994]) is given for the three tiered test. Point-biserial coefficients for nine of the twelve items show medium positive correlations (>0.3)[171], pointing to the test measuring an underlying understanding well. Results for the two-tiered test are not published[172], as the learners must be "Sure" of their answer to be marked correct. The two-tiered score and number of "Sure" answers are correlated, meaning that the results for the two-tiered test would likely be less reliable. Although the number of false-positives may be reduced using this method, increasing the number of false-negatives feels ethically and theoretically

[169] Simplifying a situation or explanation of a phenomenon, so that learners get a simplified understanding that explains the core actions. For a more in depth discussion of idealisation, with use of physical examples, see Weisberg [2007].
[170] Peşman and Eryılmaz [2010]
[171] Cohen [2013]
[172] Peşman and Eryılmaz [2010] contains analysis at the three-tiered level only.

Q	Learning Objective Tested	Situation
1	Models of Current	Simple Loop
2	Material Properties and Brightness	
3	Internal Resistance Brightness	Simple Loop with Internal Resistance
4	Internal Resistance Power	
5	Internal Resistance Voltage	
6	Internal Resistance Current	
7	Voltage Brightness	Simple Loop with Different Batteries
8	Conditions for Bulb Burning Out	
9	Summing Voltages in Series	Batteries in Parallel and Series
10	Identifying Resistors in Series	Two Bulbs (with fittings)
11	Identifying Resistors in Parallel	
12	Identifying Resistors in Series	Series, Parallel and Short Circuits with Resistors
13	Identifying Resistors in Parallel	
14	Physical Analogues for a Resistor	
15 16	Conditions for Current Flow	Black Box Device Attached to a Resistor
17	Properties of Current and Potential	Simple Loop
18	Charge Carrier and Flow Speed	
19	Charge Flow Model	
20	Brightness Comparison	Simple Loop, Two Bulbs in Parallel and Series
21	Between Situations	
22	Current Comparison	
23	Between Situations	
24	Potential Difference Comparison	
25	Between Situations	
26	Kirchoff's Voltage Law	
27	Kirchoff's Current Law	
28	Ammeter Usage	
29	Voltmeter Usage	
30	Open Circuit in Series	
31	Open Circuit in Parallel	
32	Bulb Brightness in a Mixed Circuit	Mixed Circuit with Switch and Bulbs
33	Function of a Switch	

Table 2.5: Summary of learning objectives and contexts from the Inventory of Basic Conceptions in DC Circuits developed by Halloun [2007].

questionable. Invalidating a learner's correct answer for not being sure, could lead to a gender inequality in test scores due to the propensity for male overconfidence on such metrics[173].

Although not multiple choice the Evidence-Based Practice in Science Education (EPSE) and York Science concept questions[174] are worth mentioning. They serve a different purpose, being intended for formative assessment[175] and a mix of styles of exercises. They are not exclusive to electricity and span Key Stages 2-4.

Beyond tests available in English, the Urban-Woldron Test[176] extended by two questions by Burde [2018] is a multi-tiered test with a mix of single-choice and numerical answers. This test has been used and verified in large cohorts in lower secondary as "sufficiently psychometrically sound, that it is applicable in empirical Physics Education Research"[177]. Urban-Woldron has good bases on which to make this claim. She shows, using Confirmatory Factor Analysis (CFA)[178], how given *alternative conceptions*, see Table 2.6, act as latent variables for expected answer patterns[179]. The items themselves cover a range of common *alternative conceptions* and assess the learning goals in lower secondary well, have good range of item difficulties 0.11-0.57 and have a good[180] Cronbach's α of 0.84[181]. Questions are, on the whole, concise and follow a regular pattern of informational stem plus question, making them easier to follow. The answer choices are short and simple and there are not too many of them, which reduces the reading load for lower secondary learners. This was also the test used to verify the efficacy of the materials my intervention is based on, see Section 4.1.1.

173 Lundeberg et al. [1994]
174 Link for the website for the York diagnostic assessments.
175 Millar and Hames [2003], Millar [2016]
176 Urban-Woldron and Hopf [2012]
177 The original German, "psychometrisch so ausgereift ist, dass es auch für die empirische fachdidaktische Forschung verwendbar ist", from Urban-Woldron [2013].
178 For a full discussion of this see Section 3.3.4.
179 Urban-Woldron and Hopf [2012], Urban-Woldron [2014], Urban [2017]
180 Nunnally and Bernstein [1994]
181 Urban-Woldron and Hopf [2012, p. 215]

This test was hence chosen for further development for: overlap with learning goals for lower secondary, psychometric basis for diagnosing *alternative conceptions*, readability for lower secondary, as well as, maintaining comparability to previous work.

Code	Diagnosable Alternative Conception
CU	Current Use
BC	A Battery is a Constant Current Source
RN	Current is Independent of Resistance
IR	An increase in Resistance leads to an increase in Current.
PU	The Higher the Resistance, the Higher the Current Use.
LA	Local Argumentation (Looking at Individual Points on the Circuit)
SR	Sequential Reasoning (Going Through Components Step-by-Step)
PP	Problems with Recognising Parallel Circuits

Table 2.6: Alternative conceptions diagnosable by answer-combinations and their respective codes in Urban-Woldron and Hopf [2012].

For completeness, I will also refer to two German language tests that were only published after my intervention had been planned. The Two-Tier Simple Electric Circuits Test (2T-SEC Test) is a 25-item two-tiered test. Each item is assigned a topic, with many (9 of 25) items addressing Voltage[182], which is unusually high. The initial version of the test is based upon interviews, used to better understand student difficulties concerning Voltage and to supplement the Urban-Woldron test to make it entirely two tiered[183]. A test with 30 items was initially trialled with $N = 228$ learners aged 14-15 and a revised version consequently with $N = 1568$ learners aged 13-15, across Germany and Austria. Each time learners conducted a test made of 21 items in 45 minutes, with 12 core and 9 additional items from the set of 20. The final version of the test is a result of removing 5 misfit items. Although there are some answer codings given for diagnosing specific *alternative conceptions* about voltage, not all distractors developed on their basis are provided with an encoding and no analysis of the reliability of these codings are given. Rasch analysis[184] is used to characterise and evaluate the test.

[182] Ivanjek et al. [2021, p. 5]
[183] Morris [2018], Ivanjek et al. [2021]
[184] For a more in depth discussion of Rasch analysis, see Section 3.3.3.

Although the items are seen to be too difficult for the sample, reliability values are acceptable[185].

"Ein dreistufiges Testinstrument zur Elektizitätslehre", a three-tiered test-instrument for electricity specifically developed to diagnose *alternative conceptions*[186], each with a "what", "why" and confidence tier. The original version of the test included four items to diagnose each of the eight *alternative conceptions* displayed in Table 2.7, for a total of 32 items. This has since been reduced to 24 items (each *alternative conception* diagnosed through three items) with the whole test having a Cronbach's alpha of 0.94 and with the Cronbach's alpha for each *alternative conception* coding shown in Table 2.7, each showing low to good internal consistencies. That these values are not higher is perhaps unsurprising, given that we do not expect the existence of an *alternative conception* to be the only latent variable in triggering it, owing to the differing contexts of the questions. This test is as yet unpublished at time of writing, but publication is expected in the course of the year (2024).

Concept	Alternative Conception	Cronbach's α
Current	Current Usage	.79
	Battery gives Constant Current	.64
	Voltage-Current Confusion	.54
Voltage	Potential as an Absolute Value	.56
Circuit as a System	Sequential Reasoning	.83
	Local Argumentation	.61
Resistance	Parallel is Series	.64
Energy	Current is Energy	.52

Table 2.7: Alternative conceptions diagnosable by answer-combinations and their respective Cronbach's α from Groß et al. [2024].

[185] Boone et al. [2014] in Ivanjek et al. [2021]
[186] Groß et al. [2023]

Two other tests in English under the keyword electricity are BEMA and CSEM. The Brief Electricity and Magnetism Assessment (BEMA)[187] is a single-tiered concept test, which aims to test a wide range of electricity and magnetism topics. Questions 8-13 test concepts of current electricity, but only questions 8, 10 and 11 have learning outcomes even possibly relevant for lower secondary. Question 8 tests the concept of conventional current flow in an ionic solution, a theoretically potential transfer question for lower secondary. However, as neither the concept of *conventional* current nor non-electron charge carriers are commonly addressed specifically and neither learning outcome is central, question 8 is dismissed. Answering Question 10 relies on learners knowing that the resistance of an ammeter is very low, not a central learning outcome in lower secondary, so this question is also dismissed. Question 11 is, however, a good example of an item that looks at the *electricity as a fuel* and *sharing* key concepts, both relevant in lower secondary. However, in its current form, with the large number of answer options (nine) and use of greater and less than signs, it is unsuitable for use in lower secondary.

The Conceptual Survey of Electricity and Magnetism (CSEM)[188] does not test understanding of circuit electricity, concentrating on electrostatic and -dynamic concepts.

[187] Ding et al. [2006]
[188] Maloney et al. [2001]

3 *Verifying Testing Materials*

Just as a single phrase can serve to express a variety of thoughts, one thought can be expressed in a variety of phrases.

– Lev Vygotsky
Thinking and Speech

Chapter Contents

3.1 Test Validation

The concept of validity is typically subdivided into four, with each part addressing a different methodological consideration[189]. Trochim et al. [2016, p. 28] summarises them as follows:

- "*Conclusion Validity* - The degree to which conclusions you reach about relationships in your data are reasonable.
- *Internal Validity* - The approximate truth about inferences regarding cause-effect or causal relationships.
- *Construct Validity* - The degree to which inferences can legitimately be made from the operationalizations in your study to the theoretical constructs on which those operationalizations are based.
- *External Validity* - The degree to which the conclusions in your study would hold for other persons in other places and at other times."

In this section, the concept test used for evaluating learners' learning gains is evaluated. This concept test is the way in which we *operationalise* the measurement of learners' conceptions, i.e. how we elicit what we theoretically consider learners to think and make it measurable. In other words, here I examine the *construct validity* of the concept test in several ways: reviewing the content validity through the overlap of tested and taught material, pre-operationally critiquing the test using collected literature, examining usability through a interview study, using *methodological triangulation* to examine the matching rates of spoken and selected answers in a *Cognitive Interview study*, as well as, a range of quantitative post-hoc tools examining validity and reliability.

3.1.1 Taught vs Tested Content Validity

The tested outcomes are mostly in line with the National Curriculum for England[190], outlined in Table 3.2. The test is concept based, so is difficult to match onto the knowledge statements of the Curriculum and ideally the views of experts and practitioners would have been sought to ensure a sufficient overlap. However, in order to justify the use of

[189] Cook et al. [1979] in Trochim et al. [2016]
[190] Department for Education [2014]

Item No	Cur. Point	
	Imp.	Exp.
2	-	1, 2, 8
3	-	1, 8
4	-	1
6	8	1, 2
7	8	1, 4
9	-	3
10	1	2, 8
13	-	1, 2, 8
14	-	3
15	1	2, 8
16	8	3, 4
20	-	3
21	1	2
22	-	1, 2
23	-	1, 2, 8
24	1, 9	-
25	1	2, 8
26	1	2, 8
27	-	1, 8
28	-	1
29	1	2, 8
30	-	3
31	2, 6	5
32	2, 6, 9	5

Table 3.1: Urban-Woldron and Hopf [2012] and Burde [2018] Items Coded with Key Stage 3 "Current Electricity" National Curriculum for England contents as shown in Table 3.2.

the test without such evidence, I include a table in which I map these outcomes to Items in the test, shown in Table 3.1. The only curriculum point missing in test is "bulb ratings", this is also absent from the resources used in the intervention, outlined in Section 4.3.1[191]. With this one absence from both taught and tested content, we have good agreement, broadly inline with the National Curriculum for England.

191 The reason for this piece of content being missing is also outlined there.

Code	Content
1(1)	electric current, measured in amperes, in circuits,
2(1)	series...
3(1)	... and parallel circuits,
4(1)	currents add where branches meet and current as flow of charge
5(2)	potential difference, measured in volts,
6(2)	battery...
7(2)	... and bulb ratings
8(2)	resistance, measured in ohms, as the ratio of potential difference (p.d.) to current
9(3)	differences in resistance between conducting and insulating components (quantitative).

Table 3.2: A table showing the Key Stage 3 content points for "Current Electricity" from the National Curriculum for England. Numbers in brackets indicate original number of the bullet-point shown in Department for Education [2014, p. 66].

3.1.2 *A Pre-Use Critical Reflection on the Urban-Woldron Test*

70% of learners do not see the relationship between current and brightness[192], so measuring the understanding of current through the proxy of the brightness may not be reliable. This proxy is used in Items 10, 15, 21, 24, 25, 26 and 29. However, there are also items that directly ask for current in similar situations, these being Items 2, 3, 6, 13, 22, 23, 27 and 28. Having these two groupings allows for a comparison, enabling investigation into whether the relationship between brightness and current is seen by the learners or whether the words trigger other *alternative conceptions*.

3.1.3 *Ensuring Translation Robustness*

The original test items in German were translated in parallel by myself, a native speaker of English and a fluent speaker of German; and a colleague, a native speaker of German and a fluent speaker of English. These two translations were then compared and the final translation produced, in line with the *parallel translations* model using the TRAPD approach, as described in Harkness [2003, p.38], however without of

[192] Maichle [1980, p. 13]

the use of a third-party adjudicator. Expertise of both translators was established inline with ISO17100[193] that establishes the following six essential competencies:

1. Translation competence
2. Linguistic and textual competence in both the target and the source language
3. Domain competence
4. Competence in research, information acquisition, and processing
5. Cultural competence
6. Technical competence

Competency one is met by both translators as they had a good knowledge of the intended use of the translation and that although neither are qualified translators both use both languages professionally, also fulfilling competency two. Both translators have competency in physics, both academically and in a teaching setting, with experience doing both in both languages. Both translators are academics and are required to use competency four on a daily basis. As both translators have spent extended amounts of time in teaching institutions in both German and English speaking countries, competency five, cultural competence is also established. Translations were produced in Microsoft Word Tables and communicated via Email, so no technical competencies beyond that were needed, both translators met this level of technical competence.

3.2 Examining Student Conceptions in a Cognitive Laboratory Interview

To examine the operationalisation of learners' conceptions to test results, a *Cognitive Laboratory Interview*[194] study, close to the principles of a *thinking aloud* study, was conducted using the translated testing materials. In this study, learners were asked to externalise their thoughts while answering a subset of the questions on the test. This enables learners' reasoning to be observed verbally, alongside their selected answer options. Comparing these provides a way to perform a reliability

[193] Behr [2018]
[194] Leighton [2017]

check, ensuring *convergent validity*, that two methods give correlated results when attempting to measure an underlying variable, in this case learners' conceptions. Furthermore, this acts as a pilot for the use of the questionnaire in the main study and provides an opportunity to remove any usability barriers from the questions, as well as, extending the test in order to get a better idea of how our learners think. The following two research questions form the focus of this section:

TA-RQ1: Do the learners' spoken explanations match coded *alternative conceptions* from their written answers?

TA-RQ2: Are an adequate number of *alternative conceptions* coded?

3.2.1 Method

The full questionnaire consists of 24 items. To reduce fatigue three questionnaires of 12 questions were constructed. To ensure that questions were answered a comparable amount of times, even if learners did not finish the whole test, those questions at the end of "Question Packs 1 and 2" were included at the beginning of "Question Pack 3". Care was taken ensuring a range of question difficulties and topics were included in each set, the breakdown of the items including question difficulties (given as percentage of correct answers aggregated and weighted by number of learners pre- and post-test in both control and treatment groups) from Burde [2018, pp. 201 - 203] can be seen in table 3.3.

Interviewed learners were from a variety of schools: one rural British selective-school ($n_{\text{Selective}} = 17$, $\bar{t}_{\text{Selective}} = 10\text{m}37\text{s}$) and three metropolitan British comprehensive schools ($n_{\text{Comprehensive}} = 14$, $\bar{t}_{\text{Comprehensive}} = 18\text{m}08\text{s}$). Learners were a mix between years 7 to 9 (ages 11 to 14) as well as pre- and post-instruction, an overview can be seen in Table 3.4. Learners self selected for participation and their parents or guardians provided consent to participate. They received positive feedback regardless of the correctness of their answers and were encouraged to provide an explanation or some underlying thoughts when none were given. This is of course different to how feedback would be given during normal teaching and on reflection, always providing positive feedback

Item No.	Topic	Difficulty (%)	In Question Pack:		
			1	2	3
2	I/R	51		✓	✓
3	I/R	38	✓		✓
4	I	58	✓		✓
6	I/R	16		✓	✓
7	I	39	✓		
9	P	27	✓		
10	I/R	49		✓	
13	I/R	46		✓	✓
14	P	23		✓	✓
15	I/R	46	✓		
16	I	24	✓		
20	P	24	✓		✓
21	I	36		✓	✓
22	I	58	✓		
23	I/R	19		✓	
24	I	28	✓		✓
25	I	49	✓		✓
26	I	39		✓	
27	I/R	16	✓		
28	I	43		✓	
29	I/R	47		✓	
30	P	22		✓	✓
31a	V	14	✓		✓
31b	V	10	✓		✓
32a	V	11		✓	
32b	V	5		✓	

Table 3.3: Table showing the breakdown of items into sub-questionnaires for validation through thinking-aloud. Topics are Voltage (V), Current (I), Resistance (R) and Parallel Circuits (P). Difficulties given as percentage of students that correctly answered aggregated across both pre- and post-test in the interventional study from Burde [2018].

Selective	Year 8 (Pre-Instruction)	8
	Year 9 (Post-Instruction)	9
Comprehensive	Year 7 (Pre-Instruction)	7
	Year 8 (Post-Instruction)	7

Table 3.4: Table showing the number of learners pre- and post-instruction in each school type.

may result in the learners adhering to their first answers. This is not necessarily negative in this situation where *alternative conceptions* are under investigation, as it is these initial responses that are of interest.

To begin each interview, the following passage was read and some demographic questions were asked to the learner:

> Hello, (insert learner name), My name is Tom and I work at a University. It's my job to try and understand how people think about science. Anything we talk about today won't be used by your teacher and is not a test. I'm interested in how you think, not what you know. I'll be recording the sound from our talk, so that I don't forget anything you said. Is that okay with you? If you want to stop at anytime, you can tell me and we'll stop straight away and when I write my research you'll be able to look at it too, if you want to.
>
> 1. What school year are you in?
> 2. Have you learnt anything about electricity in school before?
>
> Let's practice thinking aloud. Say aloud everything that goes through your mind, whilst finding an answer to the question. Could you please try and estimate how many seats there are in your science classroom?
>
> Now, I am going to show you some questions on electricity. Don't worry if you don't know how to answer them. Like I said, I'm not here to test you, just understand how you think. So, if you could read the first question aloud and then you can try and solve it. If you don't understand the diagrams, I will help you by telling you what each of the symbols mean. Whilst you are solving the questions, try and say everything that goes through your mind out loud.

Although the learner was asked to "think aloud" this is technically not a "thinking aloud" study, as defined by Leighton [2017], as in addition to positive feedback for displaying their thoughts, I also asked *process-oriented probes*[195], a reflection on this style of interviewing will be given later in 3.2.9.

[195] Defined in Willis [2015] as questions intended "to uncover the rationale underlying a given response (e.g., "Can you please tell me how you arrived at your answer?")"

All interviews were audio recorded and then transcribed using an AI-tool, otter.ai[196], then being manually checked. Each utterance was then coded by myself in a first pass using the alternative conceptions coded by the test. Then on a second pass with a larger range of possible alternative conceptions from wider literature and inductively from the arguments learners made. Special attention was paid that conceptions are coded beyond superficial factors such as use of physical vocabulary, as despite the use of subject specific vocabulary and referral to physical rules, post-instruction learners display the same ideas as are present in the pre-instruction learners[197]. However, these can be harder to detect due to the superficial factors previously mentioned.

3.2.2 *Typical Examples of Interview Responses*

The following is an example of a coded section of interview from a pre-instruction learner (Taken Day 1, Interview 1, hence 1-1) answering Item 22[198]. I am interviewing and am identified in all transcripts as "Tom". Item 22 asks about a simple loop circuit with a light-bulb, points A and B are marked on the wire are directly (and equidistantly) either side of the bulb. The learner answers both items correctly on the sheet and their final statements in both cases show the physical idea of current conservation, coded here in green. As the concluding statement here in both cases is a physical idea, the learner is marked as showing a physical conception in the end, despite the preceding set of statements showing four *alternative conceptions*: Current-Distance Conception, Current is Taken, Current Use and Sequential Reasoning[199]. No codes are given for uncommented reading of answer options. Text read aloud is shown in curly brackets: { }, as in the example overleaf:

[196] Liang and Fu

[197] von Rhöneck [1980, p. 25]

[198] Shown in App. A on page 235.

[199] For an overview of these *alternative conceptions*, see Table 2.2.

Time	Speaker	Transcript
03:39	1-1:	{The light bulb in the circuit below is glowing. What can we say about the current points A and B? The current is bigger at A than B. The current is bigger B than A, the current is the same at B, A and B.}
	1-1:	If we're measuring them, they will be at the same distance. So they'll capture the same current from the battery. So I think the current is the same as [sic] A and B.
04:08	Tom:	Thanks very much.
04:10	1-1:	{Give a reason for your answer. The current is the same in the whole circuit.} Yes, I think some of the current gets used up in the light bulb. Yeah, but if they're the same going around the current will still be the same on both sides. Or if the current gets used up in the lightbulb. I think it's measured before the light-bulb. This current is the same in the whole circuit.

This section of the transcript shows the *alternative conceptions* exceptionally clearly and presents a rich and explicit account of the learner's reasoning weighing up given answer options and then deciding on an answer displaying physical reasoning. This results in Item 22 for Interview 1-1 being coded, referred to as *summative codes* here, as that the learner displays a physical conception.

Some statements are more difficult to code directly. For example an answer to Item 24[200], comparing the brightness of two bulbs attached with wires to batteries, one short-circuited with a bulb in a simple loop. The same learner offers this as explanation:

Time	Speaker	Transcript
07:09	1-1:	Their cell is passing through having to go down and also around to enter both lightbulbs which take up some current as well.

Firstly, the word "cell" is not mentioned in the question and it cannot "pass through", so it is assumed that hear the learner has confused this with current or a more nebulous electricity†; this part of the utterance

[200] Shown in App. A on page 236.

is therefore coded as an Electricity† Issue. This is not an *alternative conception*, but a general problem that will be discussed later on page 87. This then "go[es] down and around" in a statement that seems to echo the logic of Local Argumentation, when taken with the diagram in Item 24. Then, this consequently "enters the light bulbs" in an example of Sequential Reasoning, where Current is "taken up", similar to Current Use. Implicit here is that there is a constant current from the battery and that this current is shared between the connected bulbs. In such a statement, where the *alternative conceptions* are not mutually exclusive or refuted, all explicit codes are given in the *summative code*. This results in the *summative code* for Item 24 for Interview 1-1 being assigned as that the learner displays local argumentation, sequential reasoning and current use.

Sometimes the use of non-standard vocabulary is, however, recognisable as a physical conception, and, as in this case, assigned a physical conception as *summative code* alone:

Time	Speaker	Transcript
01:29	2-3:	{In, er, in the circuit, a light bulb and two resistors er resistance R equals 10 ohms and R2 equals 10 ohms there is a current of 0.4A. The resistor 1 is swapped for resistor with 3, resistor 3, 20 ohms. How does this change the current through the light bulb?} Um, probably smaller than (inaudible)
02:04	Tom:	Why do you reckon it's smaller?
02:05	2-3:	Because it's the amp and it's just, um, putting more ohms in there...
02:09	Tom:	Right.
02:09	2-3:	Yeah, swapping out (inaudible).

If we were to paraphrase this using scientific vocabulary, it would read something like "We are increasing the resistance, by swapping one resistor out with a larger one. This reduces the current."

However, there are situations, like in the extract below, where even with the use of scientific vocabulary, interpretation is difficult. This explanation is given in answer to Item 4[201]. The situation under investigation is a simple loop, with ammeters either side of a motor.

[201] Shown in App. A on page 234.

Time	Speaker	Transcript
00:45	3-1:	It looks like a series circuit to me, so you don't lose any of the electrical current. So I'm going to say both ammeters share the same current.
00:55	Tom:	Great, so if you could cross, cross that with the pen, thank you. Wonderful. And then in the little grey box underneath it says give a reason.
01:03	3-1:	Okay. So, the current is the same, the whole circuit.

The first utterance seems to contain a widely physical interpretation and then a statement that would, on the surface, imply a Sharing Conception, but would read as entirely physical if the word "reading" was added to the end or if sharing is taken to mean "have in common". Interviewee 3-1 regards their second statement to follow on from the first, hence "so", reinforcing the interpretation as physical conception. This results in Item 4 for Interview 3-1 being *summatively coded* as that the learner displays just a *physical conception*, as the grounds for concluding on a *sharing conception* seem ambiguous.

Although it is necessary to reduce the complexity of the statements to enable reasonable comparisons between spoken and questionnaire answers, I hope these examples prove illustrative of the types of complexities when coding learner statements in this way.

Using this method, the interviewer seeks to minimise intervention. This resulted in a lot of vague (11%) or non-reasoned (13%) answers, coded as such and ignored for purposes of validation. As an interviewer it was also difficult to refrain from asking students to clarify statements, as I would do in a classroom, something I also did on multiple occasions. The statements arising from these are however included in the summative codes for validation. These issues would not arise in other semi-structured interviews; reflections on this are given in Section 3.2.9.

3.2.3 *Measured Alternative Conceptions*

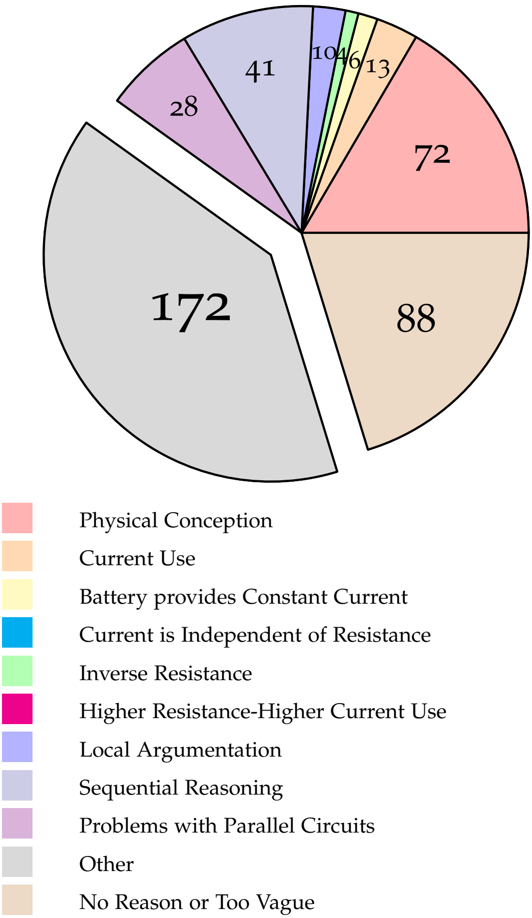


Figure 3.1: Pie Chart Showing Occurrences of Measured Summative Codes: *Alternative Conceptions* coded in Rainbow (ROYGBIV) colours. Note the missing "Current is Independent of Resistance" and "Higher Resistance-Higher Current Use", shown in cyan and magenta. The large grey segment shows "Other" ways of explaining, detailed in Figure 3.2.

As shown in the pie-chart in Figure 3.1 the measured alternative conceptions amount to 174 occurrences in total, marginally outnumbering those unmeasured by the test. The test is also capable of diagnosing the first, fourth and sixth most common *alternative conception* codes, where coding the second, third and fifth is not straightforward and discussed in section 3.2.11. This presents some evidence to suggest an adequate number of *alternative conceptions* are encoded, in partial support of TA-RQ2. In this section each will be discussed and described as found. In addition, the two *alternative conceptions* diagnosed by the test but not found in the interviews are discussed, considering reasons for their absence. Problems with parallel circuits are discussed in Section 3.2.8, as I regard the lack of clarity in the diagnosis as a generalised problem in the original Urban-Woldron and Hopf [2012] test as insufficient.

The largest group of answers matching an assignable code are the *physical conceptions*. This could be by the application of a learned rule, shown here in response to Item 22[202] with current in a simple loop:

Time	Speaker	Transcript
01:59	5-4:	{The light bulb in the circuit below was glowing. What can you say about the current at points, A and B?} (pause) So the current is the same, as it's a series circuit.

Alternatively, learners demonstrate some reasoning steps, showing the links between physical constants, such as in the following segment where the learner reasons the answer to Item 10[203] from resistance, to current, to brightness:

Time	Speaker	Transcript
00:46	5-2:	{In the circuit, there are two resistors and a light bulb connects to a battery. If we keep R2 the same, but decrease the resistance of R1 what happened to the brightness of the light bulb?} (pause) If we decrease the resistance then the current increases, so light bulb will shine brighter.

[202] Shown in App. A on page 235.
[203] Shown in App. A on page 240.

To be coded *physical conception* the reasoning does not need to be considered a model answer, simply enough to generate the correct conclusion in this situation. The following statement is coded, both *physical conception* and *local argumentation*, as despite using the logic of an *alternative conception* it provides an accurate description of the situation at hand and results in a physical answer when reasoned to the logical conclusion. This following excerpt is taken from the discussion of Item 7[204], a mixed circuit with a branching section, which is opened with a switch and turned effectively into a series circuit. The question asks how a bulb's brightness would change after this parallel to series switch happens:

Time	Speaker	Transcript
04:50	3-3:	Actually it glows brighter.
04:54	Tom:	Ah, and why would you say it gets brighter?
04:57	3-3:	Because the, all the electrons are going through it now instead of splitting fifty-fifty.

Sequential Reasoning is used frequently at 41 occurrences in answers to a range of questions, shown in Figure 3.3. The reasoning can be applied to a lot of situations and is used together with a variety of other conceptions. There are some giveaway words when students use *sequential reasoning* such as "already"[205], "after"[206] and "then"[207] when reasoning a series of events, or the reasoning can be more explicit, as in the following discussion of Item 7:

Time	Speaker	Transcript
02:56	3-1:	Oh, I think it's just gonna stay the same because it's still connected as of, mmm, I don't know, actually, perhaps (pause) um, I feel like it's gonna stay the same, but then I feel like it's not gonna turn on because the switch is there, but the switch surely would have to be at the start for that to happen.

[204] Shown in App. A on page 235.
[205] e.g. Interview 2-4 at 04:26
[206] e.g. Interview 6-1 at 08:48, Interview 8-3 at 07:03
[207] e.g. Interview 2-1 at 3:58

In this quote, the learner makes explicit reference to the sequence of the components being important. The prevalence of this *alternative conception* and the links to the following conception *current use* are discussed in depth in Section 3.2.7.

Current Use comes in three variations: *total current use* where all of the current is used (one occurrence), *partial current use* where some of the current is used (nine occurrences) and also where the degree of the use is ambiguous (four occurrences). The following example demonstrates ambiguous *current use* and then *partial current use* in an answer to Item 28[208]:

Time	Speaker	Transcript
07:22	8-2:	Yeah, less because it's used up through the light bulb.
07:25	Tom:	Ah, and why would you say it gets brighter?
07:26	8-2:	So not exactly, it'll be less than 0.2 amps. Yeah, not 0.A 'cause it's not all of it that gets used up.

These are unexpectedly low incidences, considering high incidences of around fifty percent in English speaking secondary learners in Shipstone [1985], a multiple choice study. However, they fall more inline with Gott [1984, p. 35], where British learners, aged fifteen, give written responses, 6% writing of "using up current" and 12% of "using up" generally. This illustrates the importance of the method and medium of question and answer format in triggering given *alternative conceptions*.

Local Argumentation is largely confined to the items designed to diagnose it: items 7, 16 and 24, totalling together nine of the ten occurrences. A typical example of this reasoning, well marked with the keyword "split", is shown below, as a learner describes the current in the branching circuit from Item 16[209]:

[208] Shown in App. A on page 241.
[209] Shown in App. A on page 236.

Time	Speaker	Transcript
05:06	3-1:	Um, I1 and I2 share the same er starting branch. Well, they all do, but then they split off. So ha..., if I halve the 1.2 I get 0.6 for both of the two branches that split off. For I1 and I2 I have got to split that again to, to even out so, going to say for L1 0.60 and the same for I2 and then I3 it's going to be, oh wait sorry, 0.3 for these. Then I3 is 0.6, I2 0.3 and the same for I1.

The conception, *battery provides constant current* occurs across a range of items: 8 occurrences over 7 different items across a range of question types. Sometimes it is used to justify current being conserved in a circuit, for example this question with two ammeters either side of a lightbulb in Item 28[210]:

Time	Speaker	Transcript
03:27	6-3:	(...) {What current does the ammeter A2 show?} They'll show the same.
03:52	Tom:	Okay... and why would they show the same?
03:54	6-3:	Because they have the same like, um, battery, I'm pretty sure, yeah.

Other times it is used to justify current not changing when the load is changed, in this example looking at a second motor being added to a series circuit in Item 6[211]:

Time	Speaker	Transcript
08:54	3-2:	(...) (pause) If the current would to stay the same because the battery's still the same.
09:31	Tom:	Okay.
09:32	3-2:	So the current wouldn't change.

Inverse Resistance is used by two learners and only one of these uses it to justify their final answer to a question, but repeats this on three occasions. This learner is post-instruction so this likely results from the rule being misremembered as "the higher the resistance, the higher the current"[212] and either directly quoted or paraphrased in their answers.

[210] Shown in App. A on page 241.
[211] Shown in App. A on page 244.
[212] Interview 7-5 at 11:16

Current is independent of resistance was not encoded once, as in every answer the resistance is identified as changing something. Even in the cases where current was stated as staying the same, this was despite not because of the resistor changing, either using *sequential reasoning* or a *clashing currents* justification.

Higher Resistance-Higher Current Use is also uncoded, as *current use* is only invoked in relatively few cases and in only once where there is a resistance change. Arguably this code is implicit in this one case, as shown below, even though the link that adding a second resistor in series results in a higher resistance is not explicitly stated and the conception could be more resistors use more current - rather than an underlying concept relating to the physical constant. This statement, in answer to Item 32[213], lacks any proportional, explicitly comparative nature, so remains, I would argue, ambiguous enough to justify not coding it:

Time	Speaker	Transcript
08:26	Tom:	Okay. What does the ammeter to show us?
08:30	1-4:	Er, it shows us the current.
08:34	Tom:	Uhuh.
08:35	1-4:	The resistor uses some the current, it will be lower, I think

3.2.4 *Explanations Unrelated to the Physical Situation*

On occasion, learners justified their answers in ways unrelated to the physical situation. One pre-instruction learner, with the longest and most complex (in terms of most unique and varied reasoning) transcript, justified ticking multiple boxes. They similarly *identified missing knowledge* two other times when the question asked about resistance. In this following segment, the learner assesses the logical consequences of two possible definitions of resistance, reflecting on Item 29[214]:

[213] Shown in App. A on page 243.
[214] Shown in App. A on page 241.

Time	Speaker	Transcript
07:29	7-2:	It could get brighter depending on what resistance is. If resistance, if resistance, if resistance equals ... um.. it multiplies,
07:39	Tom:	Mmm.
07:40	7-2:	... then the light bulb gets dimmer, but if the resistance diminishes, then light bulb gets brighter.
07:45	Tom:	Right.
07:46	7-2:	I might tick both.
07:39	Tom:	Okay.
07:40	7-2:	Because it really depends on what it means.

Three learners, for a total of three occurrences, also took the *only numbers given* and proceeded to give an answer on that basis, similar to the unwillingness to reason qualitatively difficulty outlined on page 44. This is shown where the learner is looking for a calculation that can be done, but justifies their answer with the lack of information meaning that the situation cannot be more complex. As illustrated by this excerpt from an answer to Item 4[215]:

Time	Speaker	Transcript
01:12	5-1:	Uh, I'm trying to see if there's a way that I could figure out maybe one of the currents or something?
01:19	Tom:	Ahuh.
01:19	5-1:	...and then I would have a look for the other one, or just see if they're the same.
01:25	Tom:	Ahuh.
01:25	5-1:	(pause) I probably would have a guess that it'd be both ammeters share the same current.
01:41	Tom:	Okay, great.
01:42	5-1:	... because they're not saying a number.

All of these codes are counted and tabulated with the diagnosis answer options given in Urban-Woldron and Hopf [2012] and used as a *convergent validity* measure discussed in Section 3.2.6.

[215] Shown in App. A on page 234.

3.2.5 *Unmeasured Alternative Conceptions*

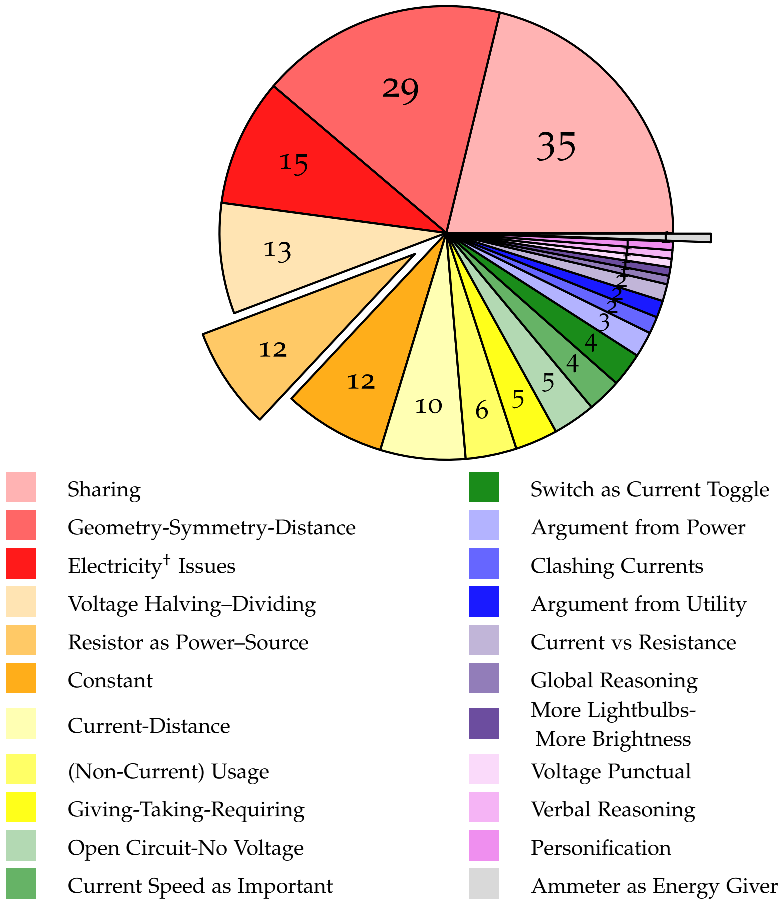


Figure 3.2: Pie Chart Showing Occurrences of Unmeasured Summative Codes: exploded segments denote ideas not present in the literature.

In this section I will discuss the *alternative conceptions* or broader difficulties that learners showed that were not diagnosed by the test, some of which are found in previous literature, to varying degrees, and some not. An overview of all 22 codes, or code groups are shown as a pie chart in Figure 3.2, exploded segments show concepts not found in the literature. Concepts are listed from high to low occurrence rates. Of note is that the sum of occurrences in Figure 3.2 does not match "Other" in Figure 3.1, due to removal of explanations not related to the physical situation, discussed in 3.2.4.

Sharing was seen as a key idea in thirty-five occurrences in 22 of the 31 interviews, excluding the times sharing is used to explain a physical idea. Many physical quantities were argued to be shared: current (13 occurrences plus 1 as charge), voltage (11 occurrences), power (3 occurrences) and energy (2 occurrences). Alternatively, learners argued ambiguously with the idea of something being shared (6 occurrences). All but one reference to *voltage sharing* were in answers to Items 31 and 32. These answers were from both pre- and post-instruction learners. Sometimes the *voltage sharing* conception is used in a close to physical way, as in this response to Item 31[216]:

Time	Speaker	Transcript
07:49	6-3:	{We now put another of the same light bulbs between point 3 and 4. How high is the voltage in the circuit with two light bulbs?} (pause) It's the same between 1 and 2, because there's no lightbulbs but between 2 and 3, I'd say it's 3 because it needs to share out the diff.... for 2.

The spoken answer here seems physical, but the learner has already said that voltage is constant in the previous part, meaning it is initially seen as 6V, then drops to 3V when "share[d] out" between the additional light bulbs. In some answers learners ignore whether there is a circuit component and simply share the voltage over the markers. Again in response to Item 31[217]:

[216] Shown in App. A on page 238.
[217] Shown in App. A on page 238.

Time	Speaker	Transcript
06:22	4-2:	{For the following circuit, how high is the voltage potentially different [sic]?} (pause)
06:45	4-2:	Would it be three?
06:47	Tom:	Why do you think it would be three?
06:48	4-2:	It's shared.
06:49	Tom:	It's shared, right, yeah.
06:55	4-2:	3 again.
06:56	Tom:	Ahuh.
07:00	4-2:	Three.
07:03	Tom:	So, why, you say it's three because why?
07:06	4-2:	They're all shared.

Some learners also state that the voltage should be "shared evenly" and yet gave numerical answers that do not support that, as in this response to Item 32[218]:

Time	Speaker	Transcript
05:46	6-3:	(reading) The following current [sic] is made from two identical lightbulbs and a closed switch. How high is the voltage potential difference? (pause) The circuit is 6 so 0.1. The difference between point 1 and 2 will be (pause) 5 (raises voice).
06:32	Tom:	How did you get there?
06:33	6-3:	I suppose because it's on the same circuit, they have to all share the same amount of, um, voltage.
06:41	Tom:	Right.
06:44	6-3:	So this one will be .7.
06:50	Tom:	Ahuh.
06:53	6-3:	This one will be 3.
06:56	Tom:	Okay, how did you get to those numbers?
06:58	6-3:	Because we would have to share equally around, when you go around the circuit, so equally you have to share around the same amount of, um, voltage.

When looking at cases where physical properties other than current and voltage were discussed, nine of the eleven occurrences were in answers to Item 24[219]. Learners argued that something determining the brightness of the bulb (be it energy, power or undifferentiated) was being shared, and around half stated this explicitly, as in the following example:

[218] Shown in App. A on page 243.
[219] Shown in App. A on page 236.

Time	Speaker	Transcript
08:53	5-3:	{Compare the brightness of the light bulbs, L1, L2 and L3 in both circuits. Which of the light bulbs glow the brightest?} (pause) L3 because all of the energy is going to it and it's not being shared.

And it was implicit in other learners' statements, remarking that it was only "one bulb", as opposed to two in the other circuit:

Time	Speaker	Transcript
03:01	5-4:	{Compare the brightness of the light bulbs L1, L2 and L3 in both circuits. The (inaudible) bulbs are the brightest.} I'd say L3 would glow the brightest as it's one bulb and it's a series circuit.

When looking to the literature, it is possible that such statements may have been interpreted as *usage* conceptions by other researchers. However, this kind of argument with "one bulb" would imply the contrast to the other circuit with two and that some resource responsible for the brightness is therefore divided between them, presenting an implicit *sharing conception*. For a discussion of the overlap of the *usage*, *sharing* and *sequential reasoning* linguistic mismatch and an analysis of the differences across languages and question format, see Section 3.2.7.

The code group, *Geometry-Symmetry-Distance*, is constructed from three codes: Geometric Considerations (20 occurrences), Symmetry Identified (5 occurrences) and *Distances Important* (4 occurrences). *Geometric Considerations* is a varied code showing when the geometry (as opposed to the topology) of the circuit is seen as important, with a marked overlap with the codes regarding parallel circuit identification, shown in Section 3.2.8. *Geometric Consideration* was also given as a code, where learners showed some obviously geometric reasoning, but it was difficult to identify a clear argument, shown here in a response to Item 9[220]:

[220] Shown in App. A on page 237.

Time	Speaker	Transcript
08:09	7-1:	{In which of the circuits are R1 and R2 connected in parallel to the battery?} (pause) Circuit 2.
08:31	Tom:	Circuit 2. Great. Thank you. And why did you choose Circuit 2?
08:34	7-1:	Er, these ones, er, like, it's just right next to it.
08:40	Tom:	Yeah.
08:42	7-1:	These ones you have to go all the way around. This one is just ... they're just everywhere.

This quote shows a general geometric justification, followed by a learner pointing out (an absence of) symmetry in one of the circuits. Referring to symmetry in circuits ranged from this rather vague statement to "they're not the same place on either half of it"[221], clearly referencing a symmetry (breaking) to the use of the word "symmetry" itself in: "The current would be the same since that since it's symmetric."[222]. Other than these, distances were also shown to be important by learners counting squares[223] or estimating distances from the diagrams[224]. There is a wide range of questions in which reasoning in this way was carried out.

Electricity† *Issues* indicates an undifferentiated or unphysical use of vocabulary, indicating a diffuse understanding of the underlying physical concepts. These are broadly under the category of *Undifferentiated Quantities* (6 occurrences), as well as three codes where the confused quantities are discernable as *Current-Voltage* (3 occurrences), *Current-Energy* (5 occurrences) and *Current-Power* (1 occurrence). These confusions show themselves as the usage of incorrect vocabulary, in this case resistance instead of current or, more correctly, charge, shown in this response to Item 29[225]:

Time	Speaker	Transcript
04:16	3-4:	Because the resistance will go through R2...

[221] Interview 8-5 at 3:08
[222] Interview 5-1 at 8:34
[223] Interview 8-4 at 14:26
[224] Interview 7-1 at 7:18
[225] Shown in App. A on page 241.

Another way would be to jump between two separate quantities in the same explanation, as in this response to Item 6[226]:

Time	Speaker	Transcript
09:23	2-4:	Like the (pause) voltage, I guess, or...
09:28	Tom:	Okay.
09:30	2-4:	...like power.

Or in this case, in reply to Item 2[227], flatly stating resistance and current are "the same quantity":

Time	Speaker	Transcript
29:31	7-2:	Ah, I don't think that makes a difference because they're the same quantity.

In *Voltage Halving-Dividing*, split into *Voltage Halving* (8 occurrences in 2 pre-instruction, 4 post-instruction learners) and *Voltage Divides Evenly* (5 occurrences in 3 pre-instruction learners), we see a similar conception to *sharing*. All occurrences are in answers to Items 31 and 32, specifically asking about voltage. The use of the word "halving" could be seen as the application of a learnt rule. However, seeing as it occurs in both pre- and post-instruction learners and the similarity to *sharing*, a common concept outside of this topic, it seems that the conception is also informed by pre-instruction experiences. Their use of the word "halving", as in this answer to Item 31[228], sometimes implies that passing through the components seems to half a value sequentially:

Time	Speaker	Transcript
10:15	6-1:	So then 1.5 here, 1.5 here, but you would half it to make 7.25 here. So, yeah, that's 1.5, then you get another 1.5 that would be the current down here, but instead it's 0.75.

This previous segment shows the learner, when asked about voltage, discussing current halving (within the same answer voltage and power

[226] Shown in App. A on page 244.
[227] Shown in App. A on page 243.
[228] Shown in App. A on page 238.

are referenced). For other learners the halving happens more in the *sharing* sense, as with the six volt cell in Item 31[229]:

Time	Speaker	Transcript
08:47	2-3:	Okay, 6 because it's still the same cell and the battery.
08:48	Tom:	Ahuh.
08:51	2-3:	3 because it's like, halvened [sic] through it(...)

Voltage Divides Evenly is in all cases much closer to a *sharing* conception, without using the word, only varying in levels of specificity. This is expressed explicitly in a statement, again to Item 31[230]:

Time	Speaker	Transcript
11:01	7-1:	Equally divided that would be three volts there and 3 volts there.

And, formulated more implicitly, once again to Item 31[231]:

Time	Speaker	Transcript
09:42	6-1:	{Look at the following circuit. How high is the voltage?} 6 voltage. There's 4 corners each labelled 1234.
09:52	Tom:	Ahuh. (pause) What are you thinking here?
10:10	6-1:	I'm thinking about like dividing the amount of volts by 4.

A conception not found in the literature, but similar to the *inverse resistance* conception, is *resistor as power source*. Five learners (3 pre-, 2 post-instruction) held this conception and demonstrated it a total of twelve times. This pre-instruction learner makes explicit reference to the idea with regards to resistors in answer to Item 15[232]:

Time	Speaker	Transcript
03:11	1-1:	(...) If we decrease the resistance of R2 I think the, the lightbulb will shine no differently, because R1 will already be powering it.

[229] Shown in App. A on page 238.
[230] Shown in App. A on page 238.
[231] Shown in App. A on page 238.
[232] Shown in App. A on page 234.

Or, in this case, where another pre-instruction learner refers to a light bulb giving energy. It is unclear as to what, but it is working sequentially around the circuit in Item 32[233]:

Time	Speaker	Transcript
27:08	7-2:	Ah, (pause) (inaudible) passes a light bulb it could, it could gain more, more energy.
27:09	Tom:	Okay
27:09	7-2:	Because light bulbs give energy.

These learners only use the idea once, but express it clearly. The other three learners that display this conception, do so consistently over three or four questions. This is illustrated in this extended extract from a post-instruction learner, covering three consecutive Items 10, 13 and 29[234]:

[233] Shown in App. A on page 243.
[234] Shown in App. A on pages 240 and 241.

Time	Speaker	Transcript
00:40	2-4:	{In the circuit, there are two resistors and a light bulb connected to a battery. If we [sic] R2 the same, but decrease the resistance of R1, what happens to the brightness of the light bulb?} Mmm, so I think the light would get dimmer.
00:56	Tom:	Okay, and what why do you think that?
00:58	2-4:	Um, because if the same amount energy from one, like stays consistent, but the other one decreases, then I think the light would also decrease. (...)
01:14	2-4:	{In a circuit with a light bulb and two resistors with resistances R1 equals 10 ohms, and R2 equals 10 ohms, there is a current 1 equals 0.4 amps, the resistance, the resistor R2 is swapped for resistor, with R3 equals 20 ohms. What happens to the current through the lightbulb?} (pause) I think it'd be larger.
01:40	Tom:	Okay.
01:41	2-4:	... because it's more like more power here.
01:45	Tom:	So yeah, great.
01:54	2-4:	{In the circuit below 2 resistors in a light bulb connected to a battery. If we keep R2 the same but increase the resistance of R1, what happened to the brightness of the light bulb?} Think it would shine brighter.
02:05	Tom:	Okay, and why do you think that?
02:08	2-4:	Because there's more... ah. Well actually maybe not, because it's after. I think it would get brighter actually, because more power being put into the circuit.
02:20	Tom:	Okay.
02:21	2-4:	Oh the resistance! Oh, okay! Then it will get dimmer.
02:25	Tom:	Okay. So it will get dimmer because what, sorry?
02:29	2-4:	Um, because the resistance is stronger, so it's harder to get the same amount of energy.

At the end of the last excerpt the learner reassesses the word "resistance", but then reverts to their old reasoning pattern once more, later in the transcript to Item 2[235], in a less obvious way, also clearly demonstrating *electricity*† clustering:

Time	Speaker	Transcript
07:15	2-4:	{In a circuit with a light bulb and 2 resistors with resistances R1 equals 10 ohms and R2 equals 10 ohms there is a current 1 or I equals 0.4 amps. The resistor R1 is swapped for resistor R3. How does this change the current through the light bulb?} (...)
07:56	2-4:	Um, I think it will be bigger, because it's more like power being pushed through.

[235] Shown in App. A on page 243.

We see then that this conception can be applied consistently, by multiple learners and in different schools and locations. These examples also show a clear difference from *inverse resistance*, where a larger resistor means a larger current can flow. The resistances here are a provider of power or energy, rather than acting as a mediating factor. This conception may reflect the connection of a social meaning of resistance (and in this case power), as in Muckenfuß [1980, p. 35], discussed earlier in Section 2.3.5. Both words, resistance and power, have a political connotation with regards to social struggle[236] and to think that resistance would lead to power is plausible in the socio-political meaning, which would go some way to explaining this conception. This code also appears along side one of the summative codes, *Verbal Reasoning*, the only appearance of this code and linked to this idea. One learner also reasons the meaning of resistance in a socio-political way that is not related to this conception, regarding Item 29[237] likely related to the phrase 'resisting arrest', but comes to the conclusion that this would make someone "lose power":

Time	Speaker	Transcript
08:15	7-2:	Because, let's say, let's say, let's say (inaudible) let's see, someone stole a pack of doughnuts and like the police and the police catches them and then they resist them from getting it. Like let's say you're tied up and your resistance to like, like from the ropes or something.
08:33	Tom:	Yeah.
08:29	7-2:	That was you're trying like, like you're trying to like you know, lose power.

In the rest of the transcript however this learner identifies that they are unsure of what a resistor does, stating it "depends on what it means", showing that their ideas connected with resistance are not one-sided.

[236] Sato [2022]
[237] Shown in App. A on page 241.

Learners argued erroneously that a physical quantity, either current (4 occurrences) or voltage (8 occurrences), remains *constant*. In the case of *constant current*, all occurrences are from Item 16[238], which asks about the current in a branching circuit. For example:

Time	Speaker	Transcript
03:29	8-1:	{The lightbulbs in the picture are the same. The total current is 1.2 A. Write the missing current for each of the branches, I1, I2 and I3.} (pause) Wouldn't it just be 1.2 in all of them?
03:48	Tom:	Okay. Why would you say that?
03:51	8-1:	The current would be the same throughout the circuit.

The conception is seen only four times, and in three of these from pre-instruction learners. However, this example seems to suggest a previously learnt rule that is misapplied in its scope. Similarly, the *constant voltage* arguments are all contained within Items 31 and 32, that specifically ask about voltage. As both of these questions involve "single loop"-like circuits, one might think that learners are applying *current conservation* with an undifferentiated current-voltage idea, which seems to be the case for some learners, who use "it"[239] when describing what remains constant. However, this does not seem to be how learners are reasoning in all cases, with one learner drawing a contrast between how current and voltage will change, stating "I think the current may change, but I think the voltage will stay the same."[240] and another giving a definition for Voltage, "it would be six volts because voltage is just the energy the particles have"[241]. This concept is used in both pre- and post-instruction learners (2 and 5, respectively) and applied in a variety of ways showing more than what might be considered initially to be a simple rule overgeneralisation.

[238] Shown in App. A on page 236.
[239] Interviewee 4-3 at 10:06 and 10:54, Interviewee 5-3 at 07:16, Interviewee 5-4 at 06:16 and 06:41; all post-instruction.
[240] Interviewee 1-1 at 13:46, pre-instruction.
[241] Interviewee 8-3, pre-instruction, at 08:34, restated at 08:58 in contrast to a definition for current given at 05:29 as "the rate of flow".

The *Current-Distance* conception is seen in a range of learners: 5 pre- and 3 post-instruction. Learners give their reasoning expressing the expected rule, "It's got more distance to travel, so surely loses brightness."[242] and in its obverse, "If we're measuring them, they will be at the same distance. So they'll capture the same current from the battery."[243] All but one (10 of 11 occurrences) of the answers showing this conception, had questions asking about light bulbs alone - i.e circuits not containing resistors or motors, or mixtures of these. That a discussion of light might trigger distance based reasoning is physically sensible, as the perceived brightness of a light-source does depend on its distance to the observer.

Learners gave explanations that involved *(Non-Current) Usage* conceptions for voltage (5 occurrences) and power (1 occurrence). These are difficult to classify as the same as *current usage*, because of how close to a physical conception they are. In fact, the following sequence shows interviewee 5-2 arguing to a numerically correct conclusion for Item 32[244], possibly just using physically inaccurate vocabulary:

Time	Speaker	Transcript
03:39	5-2:	{The following circuit is made from two identical lightbulbs and a closed switch. How high is the voltage? Between points 1 and 2?} (pause) 0 volts, I'd assume as no, no voltage is used in the switch.
04:04	Tom:	Okay.
04:04	5-2:	Between points 2 and 3 half the half of the voltage would be used in, er, the one light bulb so it'd be a difference of 3 volts.
04:15	Tom:	Yeah, great.
04:16	5-2:	And between 3 and 4 would be the same.

242 Interviewee 3-1 at 03:38.
243 Interviewee 1-1 at 03:39.
244 Shown in App. A on page 243.

The one use of power is closer to a current consumption model or more precisely, in this case, seemingly an *electricity*† *consumption* model, as current and power seem to be combined in this answer to Item 7[245]:

Time	Speaker	Transcript
04:29	6-1:	I'd say the current through L2 gets smaller, because, mmm, there are 2 bulbs before it reaches L2...
04:37	Tom:	Ahuh.
04:37	6-1:	... so I'd say there's less power going through it because the other bulbs are absorbing the power.

Giving-Taking-Requiring is a cluster of three codes: *Current is Required* (2 summative occurrences), *Current is Taken* (2 summative occurrences) and *Giver-Taker Schema* (1 summative occurrence). These codes represent (partial) displays of the *Giver-Taker Schema*, be it that a resistor "needs more current flow"[246] or that "current goes there because of the resistance"[247], as *Current is Required*. Or further, if resistances "get"[248], "take'[249]' or "capture"[250] electricity†, as *Current is Taken*. Or, finally, a battery being the "giver of [...] energy"[251], displaying the giver side of the *Giver-Taker Schema*.

Open Circuit - No Voltage is a conception shown only in Item 32 part 2[252], the only item that asks about voltage in an open circuit, but is shown commonly in 5 of 9 reasoned answers provided showing the conception. Maichle [1980] sees this as a sign that current and voltage are not separated by the learners, whereas in my interviews this is not apparent. Although there are some answers that may suggest such an interpretation, with a discussion of current when voltage is asked for:

Time	Speaker	Transcript
04:23	5-2:	Well, the current can't flow through at all so I assume it'd be 0 everywhere.

245 Shown in App. A on page 235.
246 Interviewee 5-3 at 05:47.
247 Interviewee 7-1 at 09:53.
248 Interviewee 2-4 at 02:29.
249 Interviewee 7-4 at 07:12.
250 Interviewee 1-1 at 03:39.
251 Interviewee 7-2 at 17:02.
252 Shown in App. A on page 243.

There are also two forms of the argument that there is no voltage over the switch, but there is else where (2 occurrences) or that an open circuit means no voltage anywhere (4 occurrences). Two learners see the open point as removing an essential feature of a circuit, as in the following two examples, both as answers to Item 32 part 2[253]:

Time	Speaker	Transcript
06:19	2-2:	{Um, open the switch between 1 and 2. How high is the voltage?} Between, it's like, zero (voice raises) for all of them because...
06:30	Tom:	Okay.
06:30	2-2:	... cos there's no circuit.

Time	Speaker	Transcript
06:55	2-4:	I think it's zero for all of them because, like it's not a circuit.

These two post-instruction learners seem to see "closed-ness"[254] as a property of a circuit, and dismiss the circuit on those grounds, without reasoning with regards to current at all. This could act as impetus for the inclusion of more closed circuits in lower secondary, to expand the *scope* of the definition of circuit, beyond closed circuits, even beyond reasoning to show the primacy of potential difference, as argued later in Section 4.3.1.

Learners in seven interviews make reference to "speed", "fast" or "slow". This may be used with *Sequential Reasoning*, usually in the context that when the electricity† is at speed from the battery, it can power things well and that resistors make it slow down, such as analogies with electrons as runners. However, it can also be used in a physical way, similar to a drift velocity. This is seen in learners both in the comprehensive schools and in the selective school, with five out of the seven are pre-instruction. If this is used during non-physical reasoning, in a total for three interviews across five occurrences, this is coded as *Current Speed as Important*, shown in this extract:

[253] Shown in App. A on page 243.
[254] In contrast to a circuit with an open switch.

Time	Speaker	Transcript
02:36	3-4:	(...) {What happens to the current through the light bulb?} Um, I think it's going to be, ooh, the current is going to be, er, smaller than 0.4, I think, because if the resistance increases it's going to slow the current down.

This does not appear in the earlier literature review, as it is not mentioned repeatedly or even in the text of any of the articles cited. Only Gott [1984, p. 37] in a table of results groups "using up" and "slowing down" together, which are used by a total of 15% of 300 pupils aged fifteen. I characterise these as two different conceptions, because they show reasoning with two different central ideas, usage and speed.

Switch as Electricity† Toggle is a cluster of codes that sees the switch as able to act at distance in a non-physical way, all occurring in answers to Item 7[255]. In one case this is described as "the light bulb would stop shining, because the switch is open so wouldn't be able to travel through that section [...] of the wire"[256], despite this being on another branch. Similarly, one learner describes the switch as "restricting the flow of energy"[257] and states "(...)when you turn on the switch? It would allow more energy to pass through"[258]. One learner is even more explicit in the fact that this affects the whole circuit, "the whole circuit will be well, the currents gonna stop at one point when the switch is open"[259]. These give the impression of a switch working as it may appear to in household lighting, that the light can be turned on and off from afar, with seemingly no connecting wires or on a household appliance where a switch may even toggle between modes.

[255] Shown in App. A on page 235.
[256] Interviewee 5-1 at 04:57.
[257] Interviewee 8-3 at 03:41.
[258] Interviewee 8-3 at 03:48.
[259] Interviewee 7-3 at 08:46.

Argument from Power occurs twice[260] in pre-instruction learners and is seen as an analogue to the *argument from current*, as some semi-material that moves through the circuit. The name for this semi-material may change as before the learner has the vocabulary to reason with current, they use the everyday word power.

Clashing Currents, with current coming from both sides of the battery, is shown by three learners[261]. Interestingly, all of the uses contain the word "if" and only appear once in their answers as if this conception is not very compelling or they are trying to generate new possibilities to explain the situation.

The *Argument from Utility* is used 5 times by three learners, and is as described on page 44. The quotes sound much more natural in English than the translated French quote from Johsua [1982]. For example, in this excerpt from a response to Item 3[262]:

Time	Speaker	Transcript
02:21	2-3:	{The resistor R in the circuit shown on the left has a smaller resistance. We swap the resistor with a resistor 2, um, with a higher resistance shown on the right. What happens to the circuit?} It gets (pause)
02:56	Tom	So what are you thinking?
02:59	2-3:	Um, probably (pause) probably gets smaller but not to zero.
03:18	Tom	Right, yeah. Great stuff. Why don't you reckon it goes to zero?
03:23	2-3:	Because if it went to zero, then there'd be no current and it wouldn't make the circuit work.

One learner reasons in one question with an all-or-nothing approach to the relation between current and resistance, coded as Current vs Resistance. The following extended example shows the only use of the code, as well as the only use of the code in an answer to Item 23[263], Ammeter as Energy Giver in the *Giver-Taker Schema* as discussed earlier:

[260] Interviewee 7-2 at 08:43 and Interviewee 6-1 at 14:31.
[261] Interviewee 6-1 at 10:23, Interviewee 7-4 at 05:46 and Interviewee 8-5 at 02:19.
[262] Shown in App. A on page 239.
[263] Shown in App. A on page 242.

Time	Speaker	Transcript
15:24	7-2:	{A socket is built from a battery, a resistor and an ammeter. The ammeter, the ammeter shows us the current. What happened to the current on the ammeter when we add a second identical resistor?} (pause) So, okay, so just to simplify stuff...
16:01	Tom:	Ahuh.
16:01	7-2:	...the majority of me thinks that resistance it's what, you know, makes the light bulb go dimmer.
16:08	Tom:	Right.
16:08	7-2:	And an ammeter is what make the light bulb go brighter. (...)
16:55	7-2:	Okay, on circuit what current? So yeah, this is the battery.
16:59	Tom:	Ahuh.
17:02	7-2:	So these, these both, both of these could be like, the giver of like, the energy.
17:09	Tom:	Yeah.
17:10	7-2:	Okay. I'm like, like, I feel like, I'm like, I feel like since simply they talk about the light bulb getting dimmer...
17:19	Tom:	Ahuh.
17:19	7-2:	...in here. And then they talk about the quantity of the ammeter which will support my answer, which supports my answer the think that it's the ammeter what makes the light bulb glows.
17:29	Tom:	Okay.
17:30	7-2:	Resistance. On top of my explanation on 3.1. that resistance makes the lightbulb dimmer. (...)
17:49	7-2:	Okay, so (pause) Mmmm, well, this is, well, let's do the ratio.
18:05	Tom:	Ahuh.
18:06	7-2:	R2. A1.
18:08	Tom:	Yeah.
18:10	7-2:	You can see this is outnumbered.
18:11	Tom:	Right.
18:12	7-2:	And I'd say, the majority of me thinks that resistance makes the light bulb dimmer. Yeah. And the ammeter makes the light bulb lighter.
18:19	Tom:	Ahuh.
18:19	7-2:	Then it's like a weighing scale.
18:21	Tom:	Yeah.
18:22	7-2:	Not very good drawing but so 2 Rs will be heavier.
18:28	Tom:	Yeah.
18:29	7-2:	Yeah.
18:30	Tom:	See what you mean.
18:31	7-2:	So I feel like it's gonna it's gonna get smaller.
18:38	Tom:	Ahuh. Great, thank you.
18:48	7-2:	It could actually read no current flows as well.
18:50	Tom:	Okay.
18:52	7-2:	'cos it's outnumbered to the resistance.

Firstly, viewing the ammeter as providing something rather than measuring something is understandable, as it is the only component that makes current visible. Secondly, we can also see the conception that there is a kind of metaphorical balancing act that is played between the resistance and the current and whichever wins then decides the outcome, similar to the idea of 'the world is full of competing influences for which the greater "gets its way,"'[264]. In contrast to the physical, linear effect of resistance on current, *Current vs Resistance* works like a binary switch.

Global Reasoning indicates that the way a circuit is connected is unimportant. Central to reasoning in one occurrence, the learner stated "because it's [a light bulb is] still connected to a battery"[265], despite a switch being flipped, the current would remain the same.

One learner argues to Item 24[266] that *more lightbulbs mean more brightness* and ignores the composition of the circuit when asked about the brightness of lightbulbs contained within, stating:

Time	Speaker	Transcript
09:48	6-4:	Yeah, I would say, um, lightbulb L1 and L2 'cos if have L3 it will make, like less bright. If I've doubled the brightness then it might give me like more brightness.

The conception that *Voltage is Punctual* rather than comparative is hard to show with these questions as it is always asked between two points, rather than being implicit. One learner, however, seems to interpret this as meaning voltage takes the same value everywhere between the two points asked, stating that the "voltage may change through two to three"[267].

[264] diSessa [2018, p. 69]
[265] Interviewee 8-1 at 02:33.
[266] Shown in App. A on page 236.
[267] Interviewee 1-1 at 11:58.

The final summative code present is *Personification and Analogy*, which is shown in Interviewee 7-2's answer to Item 28. As I have already discussed, this learner shows complex and varied reasoning and draws on two analogies to try and describe the brightness of two lightbulbs in a series circuits. The first of which is that of runners in a race[268] and when this seems no longer satisfactory they use "electrical race cars"[269]. The conclusion they draw is "they'd be both the same, whatever happens to R is gonna happen to both of them"[270], i.e. that a change in conditions (a changing resistance) would affect both light bulbs equally.

This concludes the overview of the undiagnosed codes present summatively in answers. It is widely reflective of the literature discussed previously. However, some conceptions are illustrated in a way particular to the English language. Ideas are presented with addenda and in increased depth when compared with previous studies discussed in Section 2.3, at least those in the English Language. When compared with previous work there has been: changes in linguistic context, learner age and research recency, that will result in changes of conceptions based on prior knowledge. There are a few exceptional cases highlighted throughout this section, notably the remarkably common *Resistor as Power-Source* conception, not found in the literature. Some of these conceptions are used to develop new answer options in Section 3.2.11. Although the goal was to establish *convergent validity* for the testing and spoken outcomes, this also serves as a summary for those *alternative conceptions* present in the population interviewed.

3.2.6 Coded Interview Results vs Question Codings

As a measure of establishing *convergent validity* for the two outcomes: conception as measured by test and spoken conception. *Convergent validity* is "the degree to which the operationalization is similar to (converges on) other operationalizations to which it should be theoretically

[268] Interviewee 7-2 at 10:15.
[269] Interviewee 7-2 at 10:31.
[270] Interviewee 7-2 at 10:31.

similar"[271]. In order to establish correlation between these two nominal variables, I use Cohen's Kappa (κ_{Cohen}). In order to produce the contingency tables shown in Tables 3.5 and 3.6, a set of cases defined by Urban-Woldron and Hopf [2012] are used. Answer combinations for these are Shown in App. A.3. For the question answers, if the question is unanswered or answered ambiguously (i.e. multiple boxes crossed) this is coded as `None`. If the answer combination is found, it is coded as `True`, else `False`. Similarly, with the interview answers, if there was an answer missing or answered *too vague* or *no response provided* in the answers necessary for the answer combination, this was coded `None`. If a conception to be diagnosed was shown in any of the answers necessary for the answer combination, it was marked `True` and else `False`. These corresponding cases were then used to make contingency tables. Cohen's Kappa for physical conceptions $\kappa_{\text{Cohen, PC}} = 0.58$ (82% Agreement), alternative conceptions $\kappa_{\text{Cohen, AC}} = 0.51$ (78% Agreement) and all conceptions $\kappa_{\text{Cohen, All}} = 0.55$ (80% Agreement) are then calculated for the `True` and `False` (i.e. Found vs Not Found) values, all fall within the bounds of a "moderate" Kappa Statistic as described in Landis and Koch [1977]. These are all likely underestimates, due to the fact that, if a learner finds an answer convincing and simply ticks that answer after reading it aloud, this is not counted. Considering this factor, and that some level of disagreement between spoken and written answers is expected, these statistics seem indicative of the test being able to reliably diagnose the learners' conceptions it claims to measure. The high concurrences of "No AC" and "Not Answered" in both physical and alternative conceptions result from: a high incidence of vague (11%) or non-reasoned (13%) answers and the fact only the limited *alternative conceptions* for which the Urban-Woldron and Hopf [2012] tests codes, included in Section 3.2.3, can be included. Together this is taken to establish at least moderate *concurrent validity* answering TA-RQ1 positively, improvements are made in following sections.

[271] Trochim et al. [2016, p. 132]

		Spoken Responses		
		PC Found	PC Not Found	No AC
Question Answers	PC Found	57	27	30
	PC Not Found	21	167	60
	Not Answered	0	2	442

Table 3.5: A Cross-tabulation of Physical Conceptions (PC) from Answers and Spoken Responses.

		Spoken Responses		
		AC Found	AC Not Found	No AC
Question Answers	AC Found	55	27	18
	AC Not Found	24	125	82
	Not Answered	9	60	499

Table 3.6: A Cross-tabulation of Alternative Conceptions (AC) from the Urban-Woldron and Hopf [2012] Test found in Answers and Spoken Responses.

3.2.7 *Linguistic Mismatches*

In the following excerpt, the learner exhibits Sequential Reasoning, but if we were to translate it to similarly colloquial statements in German, "power" would be replaced by "Strom" and the learner would appear to exhibit a *Current Use* conception. Hence, perhaps the lower occurrence of *Current Use* conceptions in the spoken answers in English compared with the written answer patterns, where there may be an undifferentiated electricity† use conception that need not be expressed with the word current. An example answering Item 15[272]:

Time	Speaker	Transcript
02:10	6-1:	{In the circuit below 2 resistors and a light bulb are connected to a battery. If we keep R[sic] the same, but decrease resistance of R2, what happens to the brightness of the light bulb?} (pause) I'd say the lightbulb would shine brighter.
02:35	Tom:	Right, great. Thank you. Why, why do you reckon that?
02:39	6-1:	If you decrease resistance, I'd say more power would get through?
02:43	Tom:	Yes.
02:43	6-1:	Lighting it up more.

[272] Shown in App. A on page 234.

The code for *Sequential Reasoning* (42 counts) is the second most common after that for the *Physical Conceptions* (79 counts) and much more common than all of the *Usage* conceptions combined (17 counts). This might call into question whether we are actually measuring the conception with the answer pairings. Figure 3.3 shows the coincidences between the items that have answer pairings that diagnose *Sequential Reasoning* and *Usage* Conceptions and the codes on students' spoken responses. The Figure shows strong connections between *Sequential Reasoning* and a large number of items, among them the items that diagnose it. *Usage* Conceptions are strongly connected to only the items that code for them. The other group connected strongly to them are the *Sharing* conceptions, particularly Item 21 that contains the word share in one of its answer options. Including *Sequential Reasoning* as *Usage* only changes one diagnosis, marginally improving correlation between answer patterns, shown in blue in Table 3.7. Again, including *Sharing* conceptions in the diagnosis of *Current Usage* and comparing with answer behaviour shows very little impact on the diagnoses questions, changing only one diagnosis, marginally reducing the correlation of answer patterns - see red arrows in Table 3.7. Overall the "ask the same question" approach[273] to questionnaire adaptation seems to have worked here, reflected in both written and spoken answers, but we can see a mismatch between the ideas as discussed by German- and English-speaking learners.

		Spoken Responses			
		CU Found		CU Unfound	No AC
Question Answers	CU Found	4	← 1	5	5
	CU Unfound	3	← 1	22	8
	No Answer	0	← 3	7	70

Table 3.7: Current Usage (CU) Conception from Answers and Spoken Responses. Arrows show the change in co-occurrences if *sequential reasoning* or *sharing* are taken to mean usage, blue and red respectively.

273 Harkness [2003]

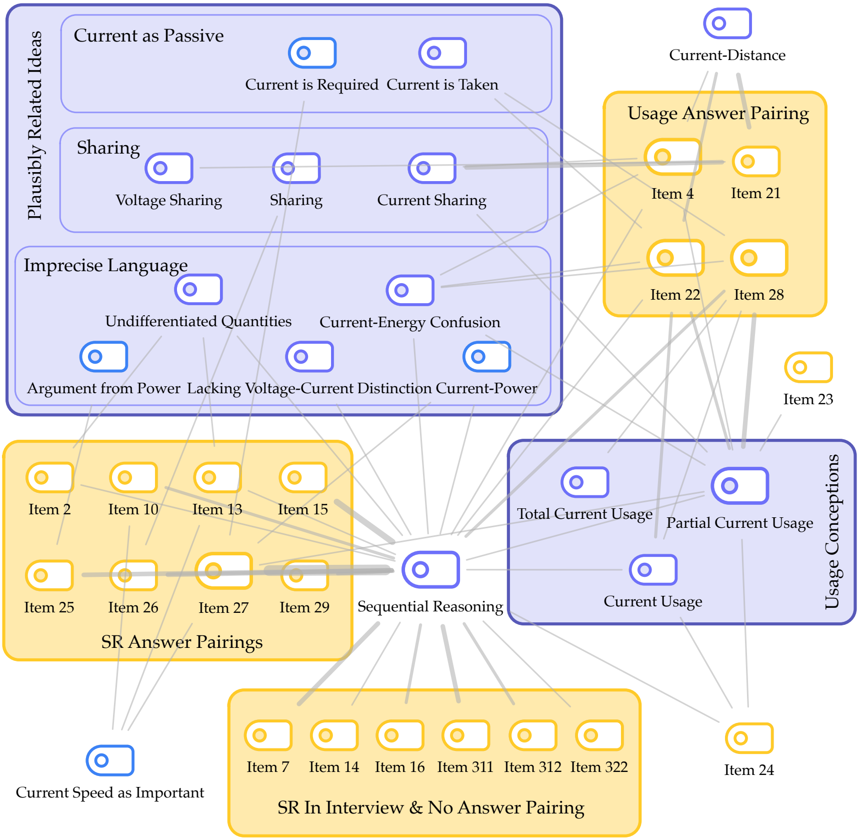


Figure 3.3: Coincidence map of Sequential Reasoning Codes, Usage Conception Codes and the Questions intended to diagnose them. Yellow tags are for items, purple tags are deductive categories and blue tags do not appear in the literature review. Line thickness indicates number of co-occurrences ranging from 1 - 8.

3.2.8 Problems with Parallel Circuits

There are 15 instances of learners justifying their answers with some variation of the definition of parallel lines, a misconception coded as *mathematically parallel*. Some occurrences of this are very explicit, for example in answer to Item 14[274], where this learner gives an extended and complete definition of parallel lines:

Time	Speaker	Transcript
14:42	7-2:	So, so, definition of parallel is two lines that never touch no matter how much they elongate or extend.
14:51	Tom:	Wonderful.
14:52	7-2:	Yes. So I think that's R1 and R3 since they're, since they're facing each other.

However, other learners' definitions were less complete, but all made explicit reference to parallel lines or a feature of the mathematical definition, as the following example, also to Item 14[275]:

Time	Speaker	Transcript
12:03	1-3:	Which resistors are connected in parallel to each other? I think R1 and R3 because they're kind of next to each other, like parallel lines would be.

Four learners also make a similar argument from geometry, but do not invoke a (partial) definition of parallel lines. Instead, justifying their choice made with the word "opposite" or, in one case, "facing each other", referred to as *parallel as opposite*:

Time	Speaker	Transcript
4:39	6-3:	Because for them to be parallel they would be opposite. None of them, none of them, none of them are on opposite sides.

[274] Shown in App. A on page 242.
[275] Shown in App. A on page 242.

Secondly, learners apply incomplete definitions or heuristics for identifying parallel-ness as either: the *opposite of series*[276], "loops"[277] or identify components as "on different branches"[278] or on "two different wires"[279]. These situationally correct heuristics are either misapplied or learners are unaware that their definitions also apply to short circuits, which may have branches through which no current flows, so do not fulfil the definition of a parallel circuit, leading to the wrong conclusions.

Finally, there is simply the confusion of parallel and series that happens in 2 answers.

This serves as a basis to understand more in depth the *problems with parallel circuits* diagnosed by the test. The *mathematically parallel* conception from first year French teaching undergraduates[280] was also found to be prevalent in early-secondary British learners. These interviews also serve to identify the markers of the learned or intuited partial definitions and the vocabulary that the learners use to express these. In a novel addition to the geometric definitions of parallel, the keyword "opposite" is also used as a basis on which to develop further distractors and extend the test, as shown in Section 3.2.11. Other - and in some situations correct - heuristics show the perils of teaching learners rote definitions without developing sufficient *span* through extended practice, which would enable learners to deal with new or unusual situations consistently.

[276] Interviewee 2-1 at 11:12 and Interviewee 3-3 at 7:51.
[277] Interviewee 8-1 at 4:26 and Interviewee 8-3 at 10:50.
[278] Interviewee 1-3 at 5:30.
[279] Interviewee 5-3 at 7:06.
[280] Caillot and Chalouhi [1984]

3.2.9 *A Critical Evaluation of the Interview Method for Evaluating Alternative Conceptions*

There are a few key differences between thinking-aloud style interviews (usually intended to assess problem solving) and other semi-structured interview methods for assessing understanding, the latter of which are called "Cognitive Laboratory Interview Procedures" by Leighton [2017]. *Thinking Aloud* interviews have minimal intervention and must involve a task of medium difficulty that evokes a problem solving response. The interviewers only intervention is to prompt the learner to "keep on talking". "Cognitive Laboratory Interview Procedures" are a wider class of interviews with the aim to examine learner comprehension and understanding and are freer to use a range of questioning tactics and prompts. Therefore, I would like to reflect on the use of the method used in my study for the purpose of examining learners' conceptions, referencing other comparable studies. To refresh the reader, the interviewer prompted in two ways: providing positive feedback when the learner explains their thinking and asking a "why" question when a learner selects an answer option without explanation.

There are several more in depth accounts and comparisons of these methods[281], but here I concentrate on their usage within subject specific education research with the purpose of eliciting learners' understanding, rather than problem solving methods. In order to give some context of what is meant by "Cognitive Laboratory Interview Procedures", the following are a few examples of researchers and key differences in their methods within electricity conceptual research: Morris [2018], Maichle [1980], Cohen et al. [1983] ask conceptual questions followed by a range of clarifying questions to dig deeper into learners' understanding; some methods like Osborne and Gilbert [1980] look to establish a relaxed dialogue with the learner; and (this time on the subject of mechanics) even some self-described thinking aloud interviews have follow-up interviews that examine learner reasoning post-hoc, as in Lin and Singh [2015].

[281] Examples include, Charters [2003], Van Someren et al. [1994], as well as the work by Leighton already mentioned.

In my method the learner is asked to read the question aloud, allowing for the *readability* and to some extent the *usability* of the questionnaire to be assessed. This is clearly not the case if the interviewer reads the question or the test paper is not filled out by the learner. Secondly, in my interviews, there were a large proportion of vague (11%) or non-reasoned (13%) responses, some of which are inevitable when not questioning more specifically, but some are due to the interviewer not always asking the necessary *process-orientated probe* or "why" questions.

The reduction of questioning, however, minimises the interviewer effect on learner thinking. Cohen et al. [1983, p. 411] states "inconsistent thinking occur[r]ed even within the context of a single question", with their 14 upper-secondary learners and I am able to observe this too, but it is very much the exception rather than the rule, as when learners show multiple ideas they seem, with few exceptions, logically consistent. The inconsistencies tend to arise when the learners read a particular distractor they find convincing, but as shown in Table 3.5, they will still reason differently to the written answers they give. This lack of interviewer imposed structure and lack of demand for specificity seems to allow learners to express their thinking in a way that produces such inconsistencies less frequently. We would expect the conditions for *conceptual change* (and perhaps evolving/inconsistent reasoning) to be made more feasible with higher levels of contingency provided by more specific questions, comparable to the shift from levels one to two outlined in Wood [2003, p. 12].

Having learners fill out a test evokes an exam-like dynamic that researchers like Osborne and Gilbert [1980] wish to avoid, but the lack of repeated questioning removes the danger of "the interview turning into an oral examination"[282], yet avoiding any dialogue-like elements increasing the interviewer effect too. Lastly, this method avoids post-hoc reflection on questions which, given the length of the questionnaire, would have probably been untenable anyway.

[282] As mentioned in Osborne and Gilbert [1980, p. 319].

In summary, if the researcher is prepared to accept some non-reasoned answers in a trade-off for learners' initial and vague reasoning, the reduction of intervention and questioning used in this way seems to produce rich data relatively unspoilt by reactivity. This would be particularly true with open-ended questions, but one would lose the usability aspect of trialling a questionnaire or translation. Tasks that induce a "high cognitive load" will interfere with verbalisation[283]. Due to the necessity of some tasks being complex in a test scenario, the researcher must allow some periods of extended silence[284], followed by a prompt such as, "What are you thinking about?" when the learner goes to pick up the pen to fill in an answer. In contrast with Thinking Aloud that distances the learner and reinforces a power dynamic with a command like "keep on talking", which could, in fact, act to distract the learner whilst they are thinking. With a similar logic, I would personally encourage researchers to extend the standard thinking aloud interjection of "keep on talking" with "Why did you answer that way?". Or, perhaps rephrasing the learner's sentence into a similar response, on a learner simply stating an answer option, in order to elicit further reasoning with minimal intervention.

3.2.10 Ensuring Usability

Thinking aloud is widely used in usability testing and part of my aim was to use the method to answer the following two usability questions:

TA-RQ3: What features of the questions are barriers to learners' understanding of what is being asked?

TA-RQ4: Are there any features acting as unintended distractors?

The first identified barrier was language; learners stumbled over the words "resistor" and "ammeter". However, as they are key topic vocabulary, there is no way to avoid them. Very few learners read "A", "V" and "Ω", as "Amps", "Volts" and "Ohms", as can be seen in Table

[283] Ericsson and Simon [1980]

[284] Not enough extended silence to induce uncertainty in learners producing multiple plausible explanations as in Hartmann [2004].

3.8. To ensure learners are able to interpret the symbols the unit is written in full on the version of the test used in the intervention.

	All	Pre	Post
Total	31	15	16
Amps	8	2	6
Volts	11	7	4
Ohms	5	1	4

Table 3.8: Number of learners reading units as their names aloud or using the name whilst discussing in Cognitive interviews, divided by Pre- and Post-instruction.

Diagrams were generally well understood, only one learner initially struggled with the use of subscripts. However, the gridded background to the diagrams, as seen in Figure 3.4, seems to have acted as an unintended distractor, with three learners reading or counting squares to determine distances. For the intervention, new diagrams were produced without the grids, in line with the German test, as can be seen in Figure 3.6 to minimise this possible distractor.

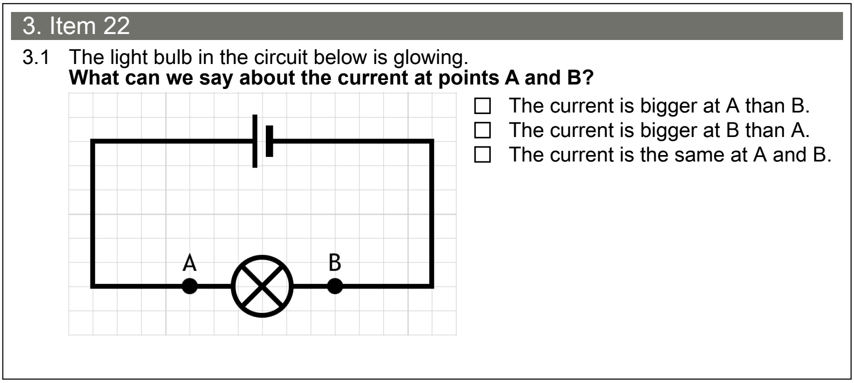


Figure 3.4: Item 22 including a diagram with a gridded background.

Learners were generally familiar with multiple choice tests. However, filling out the numerical answers in the machine readable boxes elicited four enquiries. For this reason an example was given in the main study as can be seen in Figure 3.5.

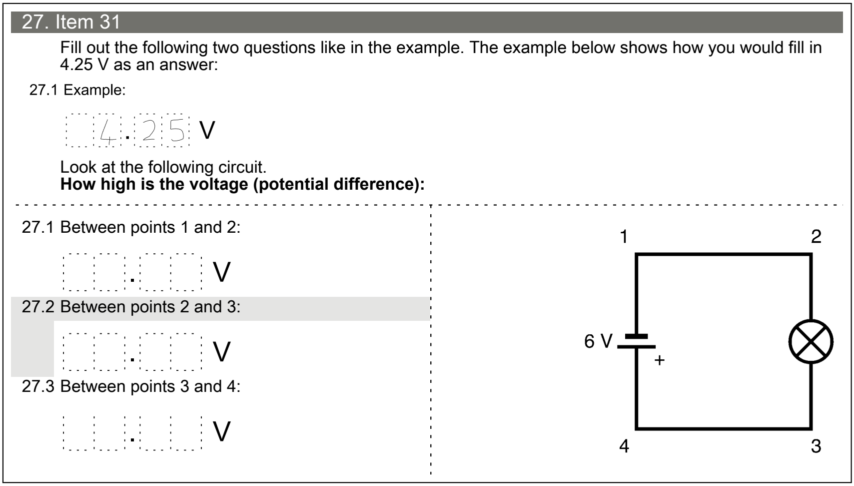


Figure 3.5: Item 31 including an example of how to fill in a numerical answer.

With these changes made, all barriers and unintended distractor features are removed.

3.2.11 *Questions and Diagnoses Added*

In order to maintain comparability with previous German-language results, I wanted to change as little on the test as possible. Ideally, only adding second tiers to questions that did not originally have them, also minimising additions to reduce any extra time and energy needed to fill out the test. This was achieved adding additional tiers to 7 items and adding two answer options to an existing second tier, no changes were made to the first tiers of any Items.

The simplest group of which to explain are the addition of a second tier to the three questions regarding parallel circuits, consisting of the answer options shown in Figure 3.6. The bottom-left answer represents the *Physical Conception*. The top-right offers a series-like answer, without having to solely apply to a series circuit. The top-left answer represents the discussed conception *Mathematically Parallel* and the bottom right

Parallel as Opposite, discussed in Section 3.2.8. The answer options are identical and in the same layout in all of the three items.

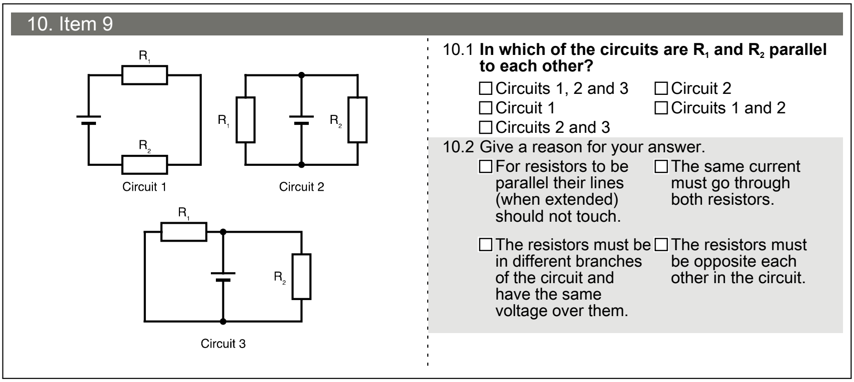


Figure 3.6: Item 9 with additional second tier post Interview Study.

Resistors as Power-Source is chosen to be added as a measured concept due to it being the most often occurring unmeasured conception that is not either an argument pattern (sharing, geometry or halving) or a more general difficulty (electricity† cluster term). This conception is tested with both resistors and lightbulbs. In Item 2, shown in Figure 3.7, the word current is used instead of power as the question asks about current specifically in order that more testwise students do not see it as the odd answer out, using the word power. We would expect this to be acceptable as learners using this conception also exhibit the electricity† cluster term. Item 13 follows a similar pattern, but resistor R_2 is swapped instead.

In Item 24, shown in Figure 3.8, we are free to use the word 'power' in the distractor, without looking like the odd answer out. The phrasing is deliberately chosen to sound colloquial, to reflect the social language of the *alternative conception*, as shown by the learners.

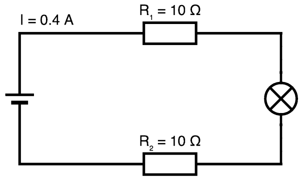
The *Giving-Taking-Requiring* idea is tricky to develop answer patterns for due to its proximity in meaning to *Current Use*. For this reason, it

5. Item 2

5.1 A circuit with a light bulb and two resistors with resistances R_1 = 10 Ω (Ohms) and R_2 = 10 Ω (Ohms) has a current I = 0.4 A (Amps). The **resistor R_1** is swapped for a resistor with R_3 = 20 Ω (Ohms).

How does this change the current through the light bulb?

- ☐ The current is smaller than 0.4 A (Amps).
- ☐ The current is the same as before.
- ☐ The current is larger than 0.4 A (Amps).



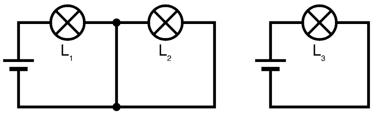
5.2 Give a reason for your answer.

- ☐ A larger resistor gives more current.
- ☐ More resistance means the current is lower everywhere.
- ☐ Current can reach the light bulb from both sides.
- ☐ The light bulb takes as much current as it needs.
- ☐ Some more current gets used up in the light bulb.

Figure 3.7: Item 2 with additional second tier post Interview Study.

20. Item 24

20.1 **Compare the brightness of the light bulbs L_1, L_2 and L_3 in both circuits (see diagram).**



- ☐ Light bulb L_1 glows the brightest.
- ☐ Light bulb L_2 glows the brightest.
- ☐ Light bulb L_3 glows the brightest.
- ☐ Light bulbs L_1 and L_2 glow the brightest.
- ☐ Light bulbs L_1 and L_3 glow the brightest.

20.2 Give a reason for your answer.

- ☐ L_1 and L_2 power each other.
- ☐ L_1 and L_3 are the same distance away form the battery.
- ☐ L_2 gets more current than the others.
- ☐ L_2 is short circuited and L_1 and L_3 have the same voltage over them.
- ☐ L_3 gets all the current from the battery.
- ☐ The current is shared between L_1 and L_2.

Figure 3.8: Item 24 with additional second tier post Interview Study.

was tested both in situations where it is in direct opposition to the idea of *Current Use* (e.g. Item 2, Figure 3.7), as well as where the *Current Use* idea would not change the answer (e.g. Item 16, Figure 3.9). The answers all use the word "need" and, again, necessitate the use of current so as not to be perceived as different by testwise learners. The answer options to Item 16 must also be sufficiently vague to not enable learners to scaffold their answer to the numerical part of the question.

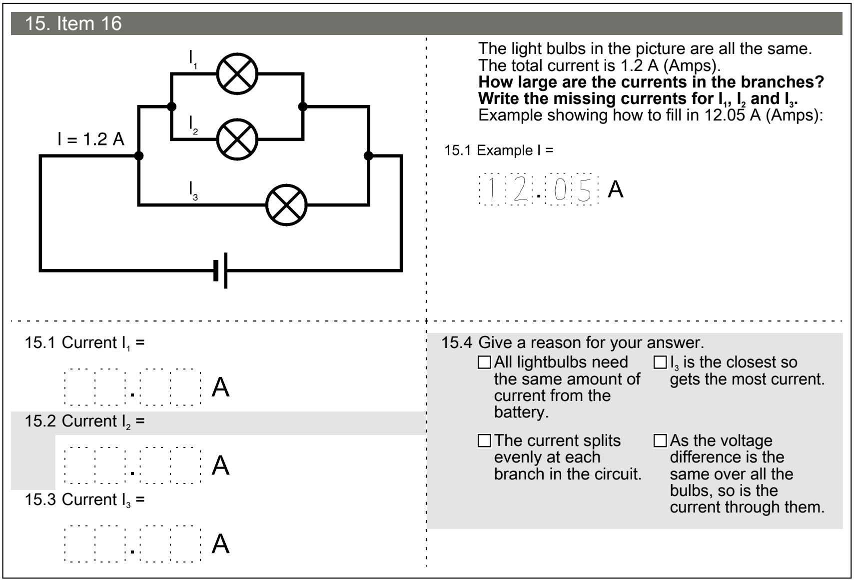


Figure 3.9: Item 16 with additional second tier post Interview Study.

In testing for the *Current-Distance* conception, it was judged important to test in a variety of situations: parallel (Item 16, Figure 3.9), series (Item 22, Figure 3.10) and short circuits (Item 24, Figure 3.8). Additionally, including an answer which demonstrates both the idea that current reduces with distance and the same rule in obverse i.e. points at the same distance (from the battery) have the same current flowing through them, as in Item 22. Item 22 was chosen as it is the only item where current is assessed at equidistant points from the battery, where there is not the possible confusion due to use of ammeters. Two answers were added to the second tier, shown highlighted in blue in Figure 3.10. Current could not be organically added to the answer so, in order to make that answer less conspicuous to testwise learners, another answer option was added referring to points A and B, reflecting the *Clashing Currents* conception. There is also a possible, already existing, answer combination for this conception in Item 21. A full list of cases for diagnosing conceptions with additions is given in Appendix A.3 and assessed in Section 3.3.

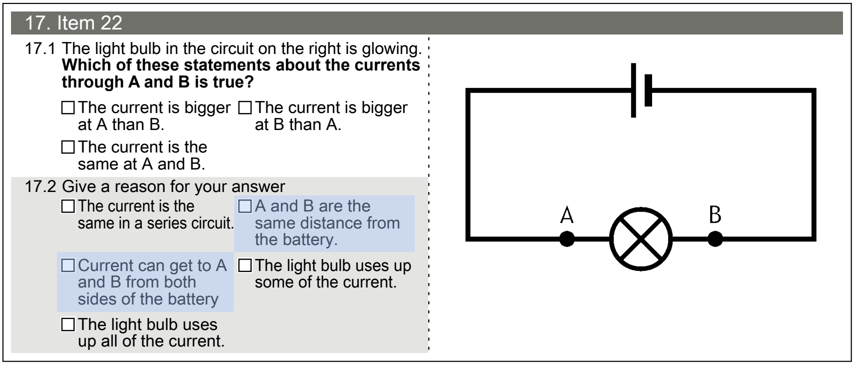


Figure 3.10: Item 22 with additions to the second tier post Interview Study, new options highlighted in blue.

In a subsequent iteration (post interventional study) and in an ongoing project, *Denkey Concepts*, adapting this questionnaire into Japanese. Three items examining learners' understanding of open and closed circuits were added. This is a key learning outcome in the primary curriculum in England[285], Wales[286] and Japan[287]. This makes questions on this topic essential for examining the understanding of pre-instruction learners at early secondary and may contribute to alleviating some of the floor effects of the test with expectedly easier questions.

[285] Department for Education [2013]
[286] Addysg Cymru [2020]
[287] Monbu-kagaku-shō [2017]

3.3 *Statistical Methods for Questionnaire Analysis*

In addition to the *cognitive laboratory interviews* for ensuring test quality, I also present the following quantitative data analysis regarding the use of the testing materials for future research. A range of methods are used to address particular aspects of reliability and suitability. Of special interest is the difficulty of the test, both in reflecting the content taught and with regards to the suitability of the method of seeking spoken elaboration in testing for difficulty. As, when learners are encouraged to self-elaborate, this has been shown to improve outcomes[288], but this is a meta-cognitive skill that not all learners (particular at ages 12-13) will have developed to do internally. Hence, in-situ test score difficulty will be higher than during *cognitive laboratory interviews*.

3.3.1 *Examining Sub-Scales with Factor Analysis*

Following Engelhardt [1997], I perform a factor analysis to identify "select groups of items that all appear to measure the same idea"[289]. Engelhardt [1997] gives very little information on how her factor analysis was completed, except for that it was analysed with the "Little Jiffy" criterion, i.e. factors are kept if their eigenvalue is over 1.

	School 1	School 2	School 3	Total
EG1	146 (6)	136 (5)	44 (2)	326 (13)
EG2	125 (6)			122 (6)
			Total	444 (19)

Table 3.9: Number of Participants included in Factor Analysis, total number shown per school, per experimental group (EG). Number shown in brackets shows number of classes.

Here, I take the post test results[290] from all schools in both intervention groups, numbers of learners and classes are shown in Table 3.9. Student answers to the redeveloped test are marked in two different ways.

[288] Chi et al. [1994b]
[289] Huffman and Heller [1995, p. 137]
[290] In line with Huffman and Heller [1995].

Firstly, using the *new* rubric. This means any additional tiers to the questions are included in the marking scheme for assigning if the question is marked correctly. For example, Item 16-d is added as an additional tier in the redeveloped test. In contrast, tests marked with the *old* rubric will mark Item 16 correct regardless of the answer to the final part in Item 16[291]. For Item 22[292], where new answer options are added, questions are marked as `NA` if they contain a new answer option, and hence, not counted when making the tetrachoric table for the factor analysis. The *new* rubric is only marked as correct if all the parts (both original and redeveloped) are correct. As we expect there to be correlation between the factors (showing some underlying understanding of the topic as a whole), an oblique (non-orthogonal) method is used here, `oblimin`, and a maximum likelihood optimisation.

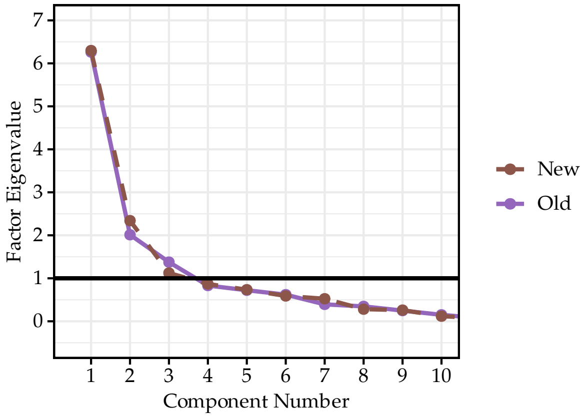


Figure 3.11: Screeplots showing post-test results the adapted test, but marked using the old and new marking criteria. The black horizontal line at $y = 1$ represents the "Little Jiffy" criterion.

[291] Refer back to Figure 3.9 for details.
[292] Refer back to Figure 3.10 for details.

The screeplots for these two methods are shown in Figure 3.11. For the *new* rubric coded data, there is a clear "elbow"[293] at Component Number = 3. This also nearly corresponds to the cut off for the "Little Jiffy" criterion (component 4 has an eigenvalue of 0.868). The data from the *old* rubric is, however, less clear cut. There appears to be two points where the gradient markedly changes, one at Component Number = 2 and one at Component Number = 4. As results become significantly more difficult to interpret at Component Number = 4, introducing a factor consisting of only two items, which accounts for only an additional 4% of the variance, it is ignored. Factor weightings for each question with each rubric where then calculated, all of those larger than 0.4[294], are shown in Table 3.10. Both sets of factors give results that can be interpreted similarly. In both cases factor F1 seems related to the questions that ask the relationship between current and resistance (corresponding to an a priori topic "I/R" in the table). Factor 2 asks about other properties of current, specifically current conservation (corresponding to an a priori topic "I" in the table) and involve exclusively lightbulbs rather than resistors. Factor 3 relates to voltage (corresponding to an a priori topic "V" in the table and branching (including parallel) circuits, this is shown by the column "Branching"). The weighting split of I16 is of particular interest, as it is both on the topic of current conservation and a branching circuit, the dual loading is, in fact, desirable. I6 and I27 both contain possibly unfamiliar apparatus, motors and a variable resistor respectively. This may contribute to their poor correlation to other items, again as Factors 1 and 2 split along lines of what the circuits contain, lightbulbs only (Factor 2) or resistors (Factor 1). I7 is only one tiered, containing a branching circuit of only light bulbs and the only question on current to contain a switch. This makes it difficult to categorise and comparatively easy to guess, perhaps, why it is not found consistently in one factor.

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[293] Where the "scree" begins and the "mountain" stops, hence the name screeplot.
[294] Hair et al. [2010] state that there is a judgement call to be made on the cutoff to be used for factor loadings. In this case, all loadings between 0.3 and 0.4 are shown in the table for completeness. The largest loadings for low loading questions are also shown.

That the above threshold factor weightings are found more consistently within these a priori categories for the *new* rubric, evidence the fact that additional tiers will ensure that questions probe a given topic and prevent guess work. Further to this, the other noted differences across the factors evidence the importance of which components seem to be in the questions and the fact that branching circuits are interpreted by learners differently.

3.3.2 *Test Internal Consistency*

Following Peşman and Eryılmaz [2010], among others, Cronbach's α is used as a measure of internal consistency for the test. Similarly to Section 3.3.1, $n = 444$ post-tests are used from across 19 classes, each with 26 items. The overall Cronbach's alpha of the new test is $\alpha_{\text{Full, New}} = 0.745$, described as acceptable, i.e. $0.7 \leq \alpha < 0.8$[295]. As marking with the old rubric produces `NaN` values in Item 22 and ignoring them would bias the Cronbach's alpha, due to the fact that it is calculated via the variance of each item and variance is dependant on n. For this reason in order to compare the answers from the two marking rubrics, Item 22 is simply excluded. Performing this calculation gives, $\alpha_{\text{!I22, New}} = 0.735$[296] and $\alpha_{\text{!I22, Old}} = 0.716$, the new marking rubric giving a marginal increase in internal consistency. Using the `cocron` package[297], these are determined to be significantly different ($p = 0.003$), i.e. the internal consistency of the new marking rubric is significantly higher than that of the old.

Gardner [1995] emphasises the importance that Cronbach's alpha should only be used when a scale is used to measure one construct. Here, it could be argued, that a single construct could be a single factor, or that "understanding of simple electric circuits" counts as a single construct. There are examples shown in Taber [2018b] that show practice in Science Education Research of reporting Cronbach's alpha for more disparately connected knowledge areas than those included here. Hence, for com-

[295] Nunnally and Bernstein [1994]
[296] !I22 means excluding item 22.
[297] Diedenhofen and Musch [2016]

			Old				New		
	Branch	Topic	F1	F2	F3	Change	F1	F2	F3
I2		I/R	0.717			T	0.709		
I3		I/R	0.500				0.621		
I4		I		0.581				0.546	
I6		I/R	(0.244)				(0.184)		
I7	Y	I	(0.185)	(-0.184)					(0.126)
I9	Y	P		-0.486		T			0.437
I10		I/R	0.549				0.467		
I13		I/R	0.794			T	0.745		
I14	Y	P			0.576				0.514
I15		I/R	0.559				0.683		
I16	Y	I		0.669		T	(-0.300)	0.541	0.463
I20	Y	P			0.574	T			(0.353)
I21		I		0.497				0.543	
I22		I		0.798		O		0.710	
I23		I/R	(0.386)				0.510		
I24	Y	I			(0.358)	T			0.605
I25		I/R	0.657				0.744		
I26		I/R	0.419				0.547		
I27		I/R	0.421	0.518			0.565		(0.381)
I28		I		0.623				0.690	
I29		I/R	0.421				0.552		
I30	Y	P			(0.381)	T			(0.242)
I311		V			0.498				0.614
I312		V			0.970				0.916
I321		V			0.686				0.829
I322		V			0.462				0.445

Table 3.10: Factor Weightings for Exploratory Factor Analysis for *old* and *new* rubrics. Branching shows questions containing branching circuits. Changed shows additions of Tiers (T) or Options (O). All weightings over 0.4 are shown, weightings above 0.3 as well as the highest weightings of below threshold questions are also shown in brackets.

Sub-Scale	$\alpha_{\text{Sub-Scale, New}}$	$\alpha_{\text{Sub-Scale, Old}}$	p	Significant
I/R ($n = 11$)	0.754	0.736	0.0075	*
I ($n = 7$)	0.488	-	-	-
I[!I22] ($n = 6$)	0.373	0.420	0.0421	
P ($n = 4$)	0.286	0.308	0.6706	
V ($n = 4$)	0.246		[Rubric Identical]	

Table 3.11: Internal Consistencies using Cronbach's Alpha for Test Sub-Scales as defined in Table 3.10. All p-values are obtained using `cocron` and significance is tested using a Bonferroni corrected level if $p = \frac{0.05}{3}$, correcting for 3 family-wise comparisons. I[!I22] shows the Current Sub-Scale (I) with the Item 22 removed due to `NaN` values.

pleteness, I report both the total internal consistencies as well as those of the sub-scales. As is summarised in Table 3.11, all factors, except the Current-Resistance (I/R) sub-scale, regardless of the marking rubric, are below the threshold for an "acceptable" Cronbach's alpha. This too we may wish to regard with caution as "while Cronbach's alphas are the standard value reported for scale reliability, this value tends to underestimate the internal consistency of scales consisting of fewer than 10 items"[298]. As the Current-Resistance (I/R) sub-scale is above this threshold number of items and the new scale has a significantly higher internal consistency, it appears that the new rubric improves the measurement of this subscale, where all other subscales remain largely unaffected. As an alternative to Cronbach's alpha Herman [2015] suggests inter-item correlation, provided Figure D.1 in the appendices.

3.3.3 *Instrument Quality with Rasch Analysis*

Following Ivanjek et al. [2021], among others, I perform a Rasch analysis to examine the instrument quality. If successful, the aim would be to assess the test with regards to a spread of difficulty suitability for the learners and provide a way to grade the test that is robust to guessing and omissions by learners. One would expect a single latent trait like *learner concept knowledge on the subject of circuit electricity* to be an acceptable model and results from the previous section suggest that is

[298] Herman [2015] in Taber [2018b]

a reasonable assumption. This enables a Rasch analysis to be carried out using the `eRm` - Extended Rasch Model[l]ing package[299]. Unlike the previous 2 sections, both pre- and post-tests are used from across 39 classes, each with 26 items, totalling $n = 932$ (an overview can be seen in Table 3.12). Each pre- and post- test is treated as if it originated from a unique learner, which allows us to examine the test in its usefulness as both pre- and post-test in producing reasonable ability scores.

		School 1	School 2	School 3	Total
EG1	Pre	146 (6)	139 (6)	45 (2)	330 (14)
	Post	146 (6)	136 (5)	44 (2)	326 (13)
EG2	Pre	151 (6)			151 (6)
	Post	125 (6)			125 (6)
				Total	932 (39)

Table 3.12: Number of Participants included in Rasch Analysis, total number shown per school, per experimental group (EG). Number shown in brackets shows number of classes.

The data was coded dichotomously, true and false, using the two rubrics (Old and New) used throughout Section 3.3. Any `NaN` responses are simply included, as Rasch analysis is robust to these. Person-Item or Wright maps for each marking rubric, *old* and *new*, are shown in Figures 3.12 and 3.13 respectively. These display that the test is significantly too difficult for the learners under instruction here, inline with the not acceptable Separation Reliabilities of the *old* and *new* rubrics, 0.4881 and 0.4653 respectively[300]. This can be seen visually in Figures 3.12 and 3.13, as a large number of *Person Parameters* lay significantly below all *Item Parameters* in both cases. The maps are to be read showing the *Person Parameters* at the top and the *Item Parameters* on scales underneath. The *Person Parameter* provides a measure of "skilledness" at a knowledge test. A learner with a *Person Parameter* of 1 would be expected to solve a question with an *Item Parameter* of 1 half the time. The higher the *Item Parameter*, the more difficult the question. As could have been predicted, the *new* rubric, with added tiers and distractors makes those items more

[299] Mair et al. [2024]
[300] To be interpreted like Cronbach's α as in Wright and Masters [1982, pp. 92-106].

difficult, increasing their relative *Item Parameters*. Items 9, 16 and 24, all where additions have been made, join the voltage items, Items 311, 312, 321 and 322 among items that have *Item Parameters* above any *Person Parameter*. This indicates the need to include easier items, as discussed already in Section 3.2.11, in any further development.

Item fit parameters given in Table 3.13, show that the fit of the model is also somewhat questionable, with 8 and 7 of the 26 Items not meeting fit parameters[301], for the *old* and *new* rubrics respectively (the failing values shown in red). Although Infit MSQs seem superficially good[302], as the questions are so hard and this could be that getting one question right will result in that dominating the assignment of a learner's *person parameter* and so bias the outlier ignoring value (Infit MSQ) towards being reliable. The very low statistics on correct answers for Items 312 and 322 make them difficult to interpret, but low values of outfit MSQs indicate possible redundancy. This is plausible due to the strong thematic relation and similar difficulties within all the voltage items (311, 312, 321 and 322). Item 27's low outfit MSQ, and hence redundancy, may come from lack of matching "person parameters", causing it to be redundant in discriminating.

[301] i.e. $p > 0.05$.

[302] Wright and Linacre [1994] gives these values for a "Run of the Mill" Multiple Choice Question as 0.7 to 1.3.

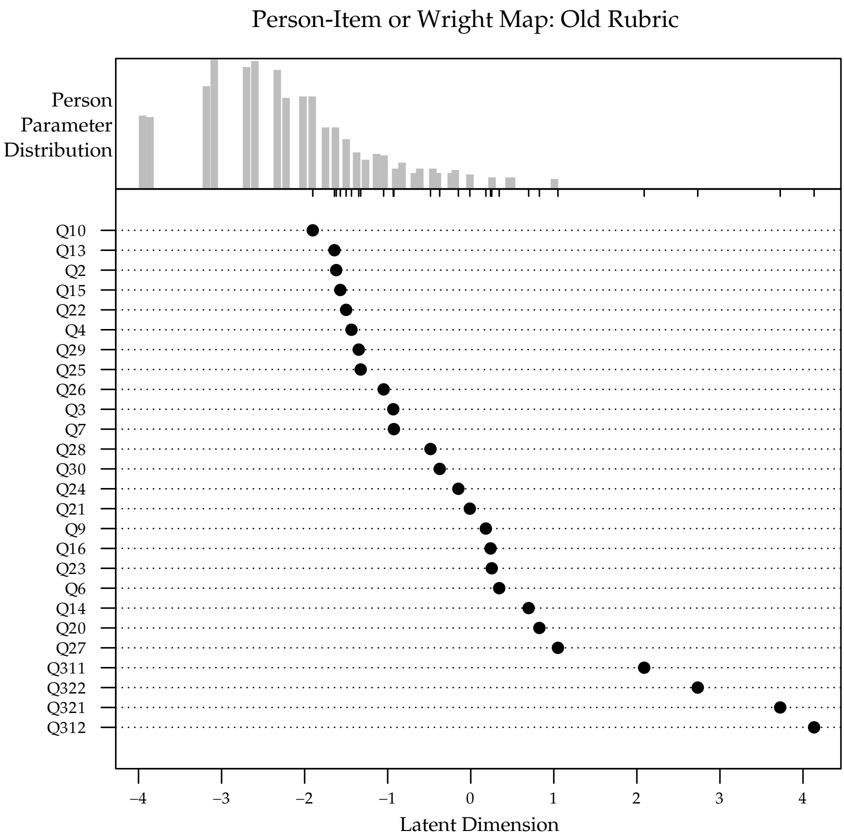

Figure 3.12: Wright Map for the Old Rubric.

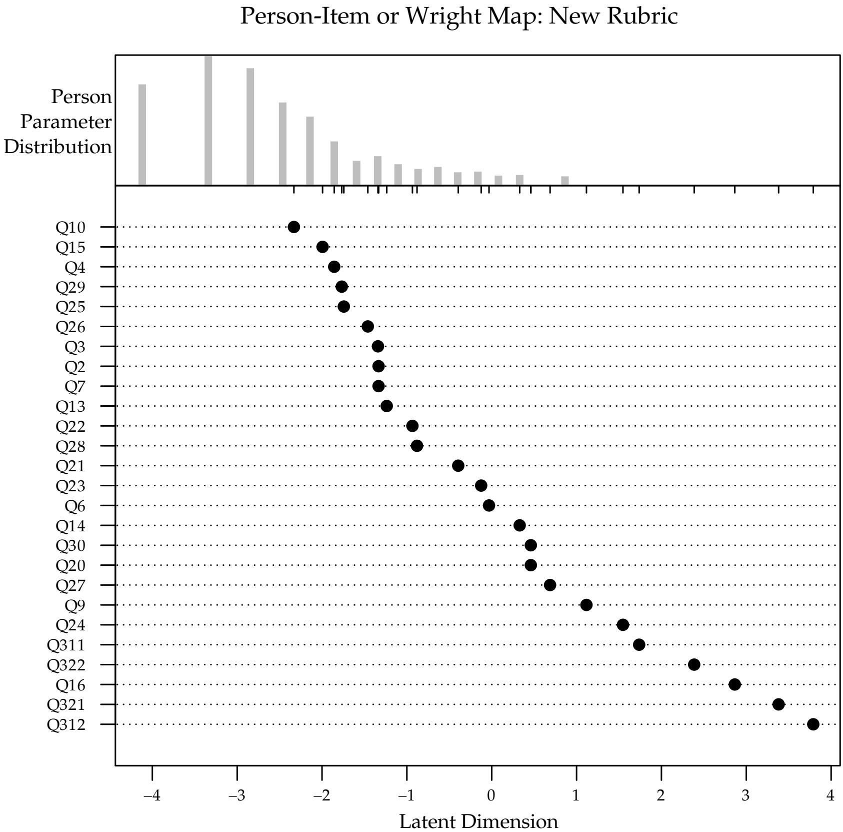

Figure 3.13: Wright Map for the New Rubric.

	Old Rubric			New Rubric		
	p-value	Outfit MSQ	Infit MSQ	p-value	Outfit MSQ	Infit MSQ
I7	0.000	1.282	1.176	0.000	1.338	1.238
I10	0.554	0.992	0.995	0.097	1.062	1.042
I14	0.000	1.500	1.032	0.000	1.536	1.063
I15	0.995	0.881	0.911	0.959	0.916	0.944
I25	0.998	0.869	0.888	0.984	0.898	0.899
I26	0.903	0.937	0.964	0.747	0.966	0.981
I29	0.971	0.910	0.945	0.904	0.936	0.960
I2	0.918	0.933	0.942	1.000	0.811	0.852
I3	0.691	0.974	0.927	0.920	0.932	0.921
I4	0.009	1.116	1.066	0.024	1.096	1.070
I6	0.000	1.181	1.051	0.000	1.203	1.102
I9	0.000	1.355	1.185	0.000	1.567	1.054
I13	0.996	0.877	0.910	1.000	0.708	0.824
I16	0.991	0.889	0.950	0.998	0.863	0.920
I20	0.000	1.256	1.000	0.000	1.312	1.026
I22	0.863	0.925	0.940	0.823	0.954	0.996
I21	0.996	0.875	0.934	0.783	0.961	0.944
I23	0.832	0.953	0.897	0.954	0.919	0.920
I24	0.014	1.107	1.064	0.977	0.905	0.952
I27	1.000	0.539	0.827	1.000	0.506	0.828
I28	0.408	1.009	0.954	0.017	1.104	0.988
I30	0.003	1.133	1.118	0.667	0.977	0.982
I311	0.996	0.876	0.924	0.401	1.010	0.922
I312	1.000	0.153	0.890	1.000	0.117	0.879
I321	1.000	0.747	0.897	1.000	0.702	0.892
I322	1.000	0.472	0.921	1.000	0.492	0.923

Table 3.13: Item Fit Statistics for Both Rubrics. Red backgrounds indicate values outside of accepted ranges.

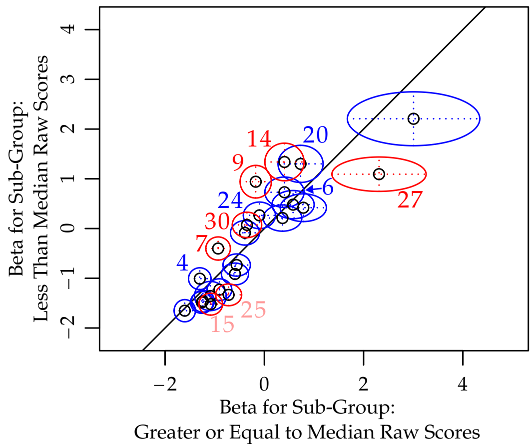

Figure 3.14: Goodness of Fit Plot for the Old Rubric.

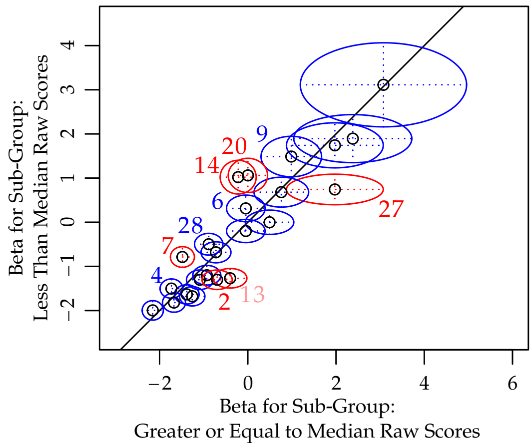

Figure 3.15: Goodness of Fit Plot for the New Rubric. For perfect alignment of item parameters between high and low scorers, items should lie along the diagonal, i.e. item parameters are the same in each sub-group. Each ellipse represents and item parameters and the errors for each group. Red circles show items whose error bars to not cross the diagonal. High contrast labels show items that do not meet a criteria in the Item Fit Statistics. Low contrast labels show acceptable Item Fit Statistics, but do not cross the diagonal.

Both rubrics result in Andersen Likelihood-Ratio tests statistics that indicate significant differences in *item parameters* for high and low ability groups. This can be seen visually in Figures 3.14 and 3.15. These Figures display the *item parameters* and their respective errors for learners that score more than (or equal to) the median on the x-axis and less than the median on the y-axis. Essentially, this analysis splits learners into two groups with high and low concept knowledge on electric circuits. If there were to be perfect agreement between the *item parameters*, they would lie along the diagonal. The high contrast labels for both show the items with poor Item Fit Statistics, low contrast labels show items where the error does not overlap the diagonal, but they have acceptable Item Fit Statistics. It is apparent from Figures 3.14 and 3.15 that there is a strong overlap of the groups. In other words there is strong overlap between items with poor Item Fit Statistics and those that show strong variation between groups, either that violate the crossing condition or are very close to doing so. I take this as the final piece of evidence that the test is not suitable for Rasch scaling. However, whether it is desirable is another question. From development of the test, one may have assumed that the test would be Rasch scalable, i.e. that a unidimensional "concept understanding" measurement scale can be established[303] and this may be the case if we are truly able to measure concept knowledge,. However, once a particular topic had been comprehended with sufficient *span*, it should be able to be applied across items. Simply put, two learners with the same "concept understanding" and sufficient *span* would perform equally well across the set of questions. However, in a test that is specifically developed on the basis of *alternative conceptions*, two learners with identical *person parameters* could feasibly find it easier or more challenging to answer groupings of given questions that align with different *alternative conceptions*. Hence, violating the invariance condition necessary for Rasch analysis. Ivanjek et al. [2021]'s test, also framed around *alternative conceptions*, returns excellent item fit statistics despite this. This could imply that a spread of difficulty, better matching the learners, could overcome this hurdle and that a weak

[303] Planinic et al. [2019]

co-correlation between items testing for given *alternative conceptions* make these possible sub-scales tolerable to the Rasch scaling process. Researchers wishing to use the test presented here further, may wish to implement it with older or higher ability learners. Or, if using it with lower secondary, add easier questions to improve the usability of the data that this test provides. On the basis of the marginal changes and the failure of both rubrics to meet necessary criteria, it is impossible to evaluate the differences between each of the rubrics on the basis of Rasch results.

3.3.4 Using Confirmatory Factor Analysis to Assess Misconceptions

Following Urban-Woldron and Hopf [2012], the test that my translation originally stems from, a confirmatory factor analysis (CFA) for each of the coded for *alternative conceptions* was carried out. This was done using the `lavaan` package[304]. The model parameters are given in Table 3.14. Of note here is that it is only possible to give goodness of fit parameters for models with four or more items coding for an latent variable. This is because there are no degrees of freedom remaining in a configuration lower than that and it essentially becomes a "three equations with three unknowns" problem, so no optimisation is necessary. It can, however, be the case that no solutions exists, as with the case of no conversion in the case of the "geometrically parallel confusion" and the "current impelled by resistances" latent variables.

[304] Rosseel et al. [2024]

Alternative Conception	Abbr.	Item	n	Conv.	SRMR	CFI	RMSEA [90% CI]
Current Use	CU	4	702	✓	0.020	0.918	0.030 [0.000, 0.087]
A Battery is a Constant Current Source	ABaCCS	4	754	✓	0.013	1.000	0.000 [0.000, 0.065]
Current is Independent of Resistance	CIIR	4	780	✓	0.109	0.629	0.368 [0.327, 0.411]
Inverse Resistance	IR	3	782	✓	-	-	-
Higher Resistance means Higher Current	HTRHC	3	787	✓	-	-	-
Local Argumentation	LA	3	629	✓	-	-	-
Sequential Argumentation	SA	4	765	✓	0.020	0.901	0.028 [0.000, 0.082]
General Problems with Parallel Circuits	GPRPC	4	750	✓	0.011	1.000	0.000 [0.000, 0.064]
Parallel Opposite Confusion	POC	3	754	✓	-	-	-
Geometrically Parallel Confusion	GPC	3	743		-	-	-
Resistors give Current	RGC	3	764	✓	-	-	-
Current Impelled by Resistances	CIR	3	684		-	-	-
Current and Proximity	CP	3	677	✓	-	-	-

Table 3.14: Table showing confirmatory factor analysis for all of the coded for misconceptions. "Conv." gives whether the model converges. SRMR is "Standardized Root Mean Squared Residual", CFI is "Comparative Fit Index". RMSEA is "Root Mean Square Error of Approximation".

For the latent variables that can be modelled, all show acceptable fit parameters, except one, “current is independent of resistance”. Acceptable fit parameters are defined by Hu and Bentler [1999] as SRMR (Standardized Root Mean Squared Residual) < 0.08, CFI (Comparative Fit Index) > 0.95, RMSEA (Root Mean Square Error of Approximation) < 0.06, also stating that older publications recommend CFI > 0.90. As the RMSEA and SRMR conditions are tested by Hu and Bentler [1999] and provide robust rejection conditions alone, I feel comfortable in accepting slightly lower CFIs. In addition to model fits, CFA gives loadings. These give a measure similar to correlation of the latent trait and the measured item encoding. There are lots of available “rules of thumb” for evaluating sizes of these loadings, but the most widely used seems to be from Stevens [2009] at Loading > 0.4. Using this, all models will be considered and discussed. Note that models with poor fit or that did not converge, are not shown. Each diagram shows the factor loading for the given answer combination used to diagnose each *alternative conception* from Table A.1.

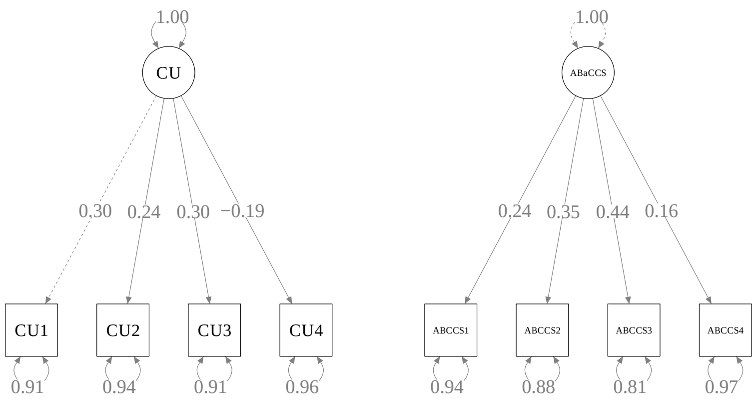

Figure 3.16: Confirmatory factor analysis loadings for *Current Use* (CU) and *A Battery is a Constant Current Source* (ABaCCS) *alternative conceptions*.

All factor loadings for *current use* codings are deemed to be weak, with *CU4* loading negatively (see Figure 3.16). In the answer options acting as distractors from *CU1*, *CU2* and *CU3* the option reads "The current is the same in the whole circuit", whereas as a distractor from *CU4* the option reads "The current is the same in a series circuit". As this is something often learnt rote during classes, this may act as a too strong a distractor to make the encoding of current use reliable. If the CFA is rerun with this item removed, the factors of the other items do not improve.

One of the factor loadings for *A Battery is a Constant Current Source* is above the threshold value and the rest show weak positive loading (see Figure 3.16). The weakest loading occurs on a question that uses motors instead of resistances (as the rest do) This would understandably change the triggering of given misconceptions, weakening the loading.

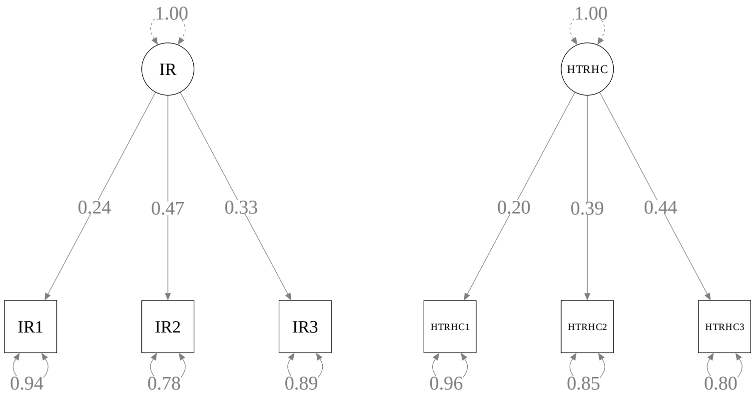

Figure 3.17: Confirmatory factor analysis loadings for *Inverse Resistance* (IR) and *Higher Resistance means Higher Current Use* (HTRHC) *alternative conceptions*.

Inverse Resistance and *Higher Resistance means Higher Current Use* load positively onto all of the answer combinations (see Figure 3.17) and the interpretation of both is very similar, as the idea of the latter is the former concept, plus *current use*. The second (or why) answer in the combinations for *IR1*, *IR2* and *IR3* are the same as in *HTRHC1*, *HTRHC3* and *HTRHC2*, respectively, partially explaining the similarities in their loadings. The higher loadings occur for Items 6 and 23, corresponding to *IR2* and *IR3* and *HTRHC3* and *HTRHC2*, where a component is being added instead of swapped out. This is a misconception triggering factor that could be considered in future research.

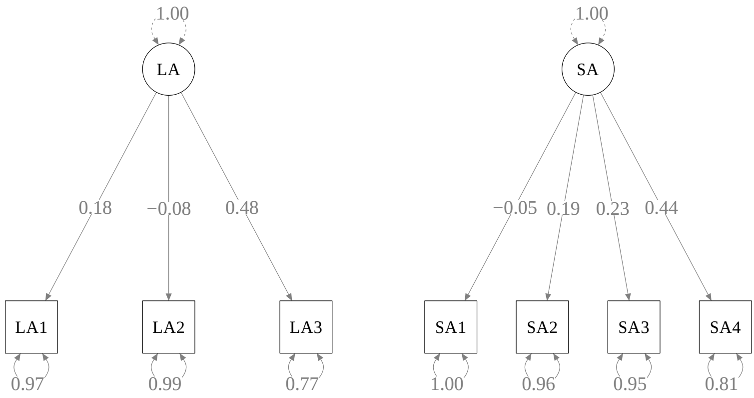

Figure 3.18: Confirmatory factor analysis loadings for *Local Argumentation* (LA) and *Sequential Argumentation* (SA) *alternative conceptions*.

The scale of *Local Argumentation* is dominated by a loading onto the third encoding with weak and even negative loadings on the other factors (see Figure 3.18). Considering that *LA2* and *LA3* are single answer encodings that have a considerably higher type I (false-positive) error rate, would mean that I would recommend that the scale be entirely redeveloped on the basis of *LA1*. *LA1* works on the basis of numerical answer inputs for Item 16 and hence would be considerably more reliable to develop a scale around.

The answer combinations for *Sequential Argumentation* are quite complex in order to account for learners holding the conception that current can flow in either direction - this, however, makes it more difficult to interpret the loadings, shown in Figure 3.18. Despite this, it is worth noting that the higher loadings are on encodings *SA3* and *SA4*, two answer combinations internal to a single item, compared to *SA1* and *SA2*, which rely on answers across multiple items and hence multiple contexts.

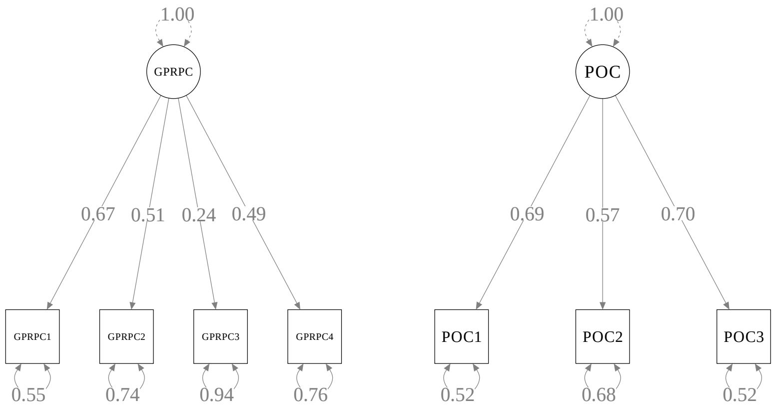

Figure 3.19: Confirmatory factor analysis loadings for *General Problems with Parallel Circuits* (GPRPC) and *Parallel Opposite Confusion* (POC) *alternative conceptions*.

All factor loadings for *General Problems with Parallel Circuits*, apart from *GPRPC3*, load strongly onto a single variable (see Figure 3.19). However, this coding defined by Urban-Woldron and Hopf [2012], is essentially just the inverse of getting the answer correct, so does not really constitute a true *alternative conception*, making it difficult to interpret.

Parallel Opposite Confusion constitutes the only latent variable loaded on highly by all answer combinations in its encoding (see Figure 3.19). The required answer combinations consist of a plausibly chosen set of circuits where the components are "opposite", and the justification "The resistors must be opposite each other in the circuit", for circuits containing resistors or light bulbs. This shows the high level of consistency of the surface level heuristic use when searching for parallel circuits and gives an indication for this being a consistently held *alternative conception*, measurable by this scale across the population. This also suggests that the teaching of identification of parallel circuits may need to be taught explicitly as this heuristic is ingrained across contexts. *Resistors Give Current* is loaded on strongly by the first two codes and only weakly positively by the third (see Figure 3.20). The *RGC1&2* both

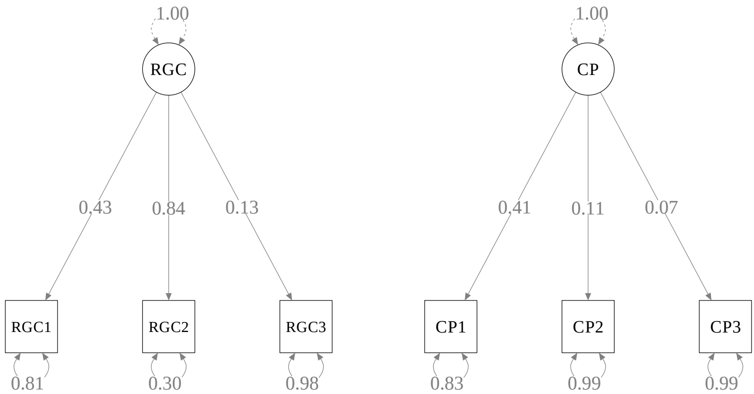

Figure 3.20: Confirmatory factor analysis loadings for *Resistors Give Current* (RGC) and *Current and Proximity* (CP) *alternative conceptions*.

use resistors in the questions, where as *RGC3* uses light bulbs. For this reason, I would recommend redevelopment of the scale exclusively on the basis of questions involving resistors.

Current and Proximity, sometimes *Current-Distance*, is dominated by the loading on *CP1* (see Figure 3.20). As stated Section 3.2.11 the conception was tested for across a variety of situations: parallel (Item 16), series (Item 22) and in short circuits (Item 24). This variation of the physical context may have led to this lack of coherence, inline with Engelhardt and Beichner [2004] and Ivanjek et al. [2021].

3.3.5 Summary of Quantitative Results

In section 3.3, it has been shown that the test used meets certain quality criteria, while others remain unmet. The entire test is shown to have acceptable internal consistency, with the redeveloped marking rubric being significantly more internally consistent than the old. This again is true for the subscale examining how current and resistance interact. No other pre-hoc sub-scale reaches an acceptable Cronbach's alpha.

Rasch analysis shows the test to be too difficult for the target learners, but not able to be Rasch scaled.

Confirmatory factor analysis shows only one scale with all factors loading well, *Parallel Opposite Confusion*, one of the newly developed scales. Despite this, indicators for the development of future tests were able to be identified. Future research may consider developing questions based on a model which extends beyond a single dimension (one *alternative conception*) to include addition or exchange of components, use of light bulbs vs resistors vs others[305], inclusion vs evasion of rote learnt phrases[306], use of dynamic vs static components[307], the direction of current, as well as the context being a parallel, series or short circuit. Also, when developing any future tests, I would recommend encoding on answer combinations within one item.

[305] i.e. Motors.

[306] i.e. "Current is the same in the whole circuit" vs "Current is the same in a series circuit.".

[307] i.e. Fixed vs variable resistors

4 *Constructing Materials for Learning*

There's no substitute for getting it right with schoolchildren first time round.

– Lee Elliot Major and Stephen Machin,
Social Mobility and its Enemies

Chapter Contents

4.1 Study Background

There is a necessity for producing new materials as traditional teaching methods do not yield a good understanding of the principles of "simple" electric circuits i.e. only 5% of technical school[308] learners have a developed understanding of current post-instruction[309], evidence that the task of teaching this topic is not trivial. von Rhöneck [1980, p. 26] claims that learners in school have no pre-existing schemata in which to integrate the term voltage. If this claim is true, which will be examined, teachers are faced with the challenging task of needing to engender real cognitive change. In the next chapter I will examine this claim, alongside some materials that have been successful in previous interventions, analysing the contributing factors. Building upon the materials and ideas in these interventions, I use theories informing instructional design, adapting materials for the context of KS3 electricity in UK comprehensive schools. Finally, the materials will be extend using an iPad application that scaffolds learner-learner talk in a research informed manner. Both of these sets of materials are used in a quasi-experimental study, of which I discuss the structure and the expected outcomes.

4.1.1 Burde's Design Based Research Results

Burde [2018] developed and tested a set of learning materials for teaching introductory electric circuits at lower secondary in German grammar schools. These materials were constructed on the basis of the *electron gas model* of electric circuits. Developed using a *Design Based Research* approach, it was shown that use of the materials improved learning outcomes in knowledge tests[310] with a medium effect strength, $d_{\text{Cohen}} = [0.70, 0.78]$ for a matched sample, dependant upon parallelisation method[311]. Additionally, Burde [2018, p. 297-8] formulated the

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308 German original: "Realschule".
309 Maichle [1980, p. 13]
310 The modified test from Urban-Woldron and Hopf [2012] discussed on page 58 and redeveloped in section 3.1.
311 Burde [2018, p. 230]

insights[312] gained into eleven suggestions for practice, listed in translation below, numbered I1-I11. Some of these are formulated with reference to theory and others are evidenced through either formative evaluation of the resources using a *teaching experiment* technique, described as *probing acceptance*[313] by Wiener et al. [2015, 2017, 2018],[314] or a summative evaluation in a quasi-experimental study comparing the new scheme of work with the status-quo.

I1. "Introduce the concepts of potential and voltage before current. This should centre voltage as a primary concept in the learners' minds, actively working against a 'dominating current concept'[315];

I2. Introduce potential as 'electric pressure' in the wires in analogy to air pressure phenomena, anchoring the concept in learners' everyday experiences;

I3. Represent the electrical potential directly on circuit diagrams with the help of an intuitive colour coding borrowed from everyday life, keeping the necessary abstraction skills as low as possible;

I4. Build on the concept of potential and introduce electrical voltage as an 'electrical pressure difference' and cause of current, promoting an understanding of the *comparative nature of voltage*;

I5. Prioritise the development of a qualitative understanding of the basic quantities of electricity and their mutual relationship, above a quantitative discussion, in introductory lessons;

I6. Use vocabulary in the formation of terms that avoids *alternative conceptions* and links to learners' everyday experiences, developing subject specific vocabulary and scientific concepts from this;

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312 Not Burde's word, he calls them "Ergebnisse" or results, appropriate for use in German, but would imply something else in English.

313 German orginal: "Akzeptanzinterviews".

314 Described as "1. Provision of Information: The interviewer explains a physical fact to the learner verbally, possibly supported by graphics and experiments. 2. Questioning Regarding Acceptance: The learner provides information on the extent to which they feel the explanation is understandable or plausible. 3. Paraphrasing: The learner recounts the explanation in their own words, while the interviewer pays attention and notes omissions and transformations. 4. Application and Practice: In the final step, the interviewee's task is to apply what they have learnt to a pertinent problem.". Translated from Wodzinski [1996, p. 41]. A more detailed description of the process is provided by it's developer in Jung [1992].

315 cf. von Rhöneck [1986a, p. 87]

I7. Analyse electric circuits on the basis of 'electric pressure differences' - voltages over resistors - and not on the basis of current splitting at junctions in parallel circuits, as this can trigger *alternative conceptions* (e.g. *battery provides a constant current*, *local argumentation* and *sequential reasoning*);
I8. Provide learners with a microscopic model of the processes in electric circuits to satisfy their epistemological curiosity for the system under instruction;
I9. Address specific examples where voltage and current **do not** occur together (e.g. an open switch). Otherwise, the relationship $V = IR$ may reinforce the *alternative conception* that *voltage is a property of current*;
I10. Promote the reflective use of models by using the bike chain model along side the electron gas model, illustrating different qualities, such as the system character of electric circuits and conservation of current;
I11. Avoid further topics i.e. internal resistances of batteries, voltmeters or ammeters, resistances of copper cables and the arbitrariness of 'earth being zero potential' in introductory lessons."

I will refer back to these insights throughout the following sections, clearly demarcating what are Burde's thoughts.

4.1.2 Burde's Materials in German

The structure and some of the key ideas for materials that form part of this study have developed over time, the initial version of the materials in German are presented in Burde [2018], of which an overview of the content is given in Table 4.1. These were then adapted into the materials used in the EPo-EKo Project[316], which I translated and adapted into English for use in this study, both of these share their content structure, which is shown in Burde et al. [2022] and summarised in Table 4.2. This section will outline the structure of the course and present the implementation of the ideas outlined in the last section. Although there

[316] A project looking at teaching simple electric circuits with potential, using contexts, as well as a mixture of the both. The materials in German can be found at einfache-elehre.de

1. Electrostatics and the Atomic Model
2. Air Currents Through Pressure Differences
3. Battery, Electric Pressure and Voltage
4. The Electric Current and Resistance
5. The Parallel Circuit
6. The Capacitor
7. The Series Circuit
8. Measurement and Calculation of Current, Voltage and Resistance
9. Consolidation and Extension Exercises

Table 4.1: Units in the intervention from Burde [2018], as given on page 8 of the original teaching guide.

are differences between the two courses, there is significant overlap between the both; the materials outlined in Burde et al. [2022] are directly developed from Burde [2018]. Burde [2018] provides teachers with a textbook, model answers and PowerPoint slides, split over 10 units. During the intervention study the topic was taught for an average of $M = 24.3$ ($SD = 9.8$) lessons[317], equivalent to $M = 18$ hours 10 mins ($SD = 7$ hours 20 mins) for a standard 45 minute lesson[318].

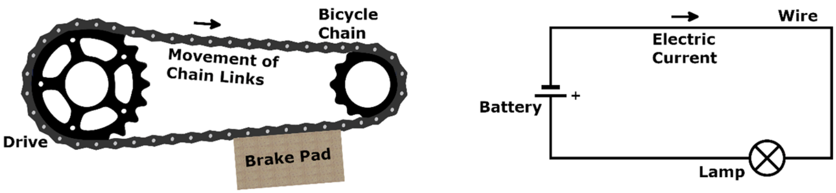

Figure 4.1: A Graphical Representation of the Bike Chain Analogy from Burde et al. [2021].

[317] Burde [2018, p. 184]
[318] This is a standard lesson length in Germany.

1. The Circuit as an Interconnected System (optional)	Using the bike chain analogy, learners learn that the electric circuit represents an interconnected system in order to challenge sequential and local reasoning.
2. Airflow from Pressure Differences	Using everyday objects as examples, e.g., air mattresses and bicycle tires, learners learn that air pressure differences are the cause for air flow.
3. Electric Pressure	The concept of "electric pressure" as a prototype of electric potential is introduced. Learners learn to colour code "electric pressure" in open electric circuits.
4. Differences in Electric Pressure	Voltage is introduced as an "electric pressure difference" and measured in open circuits using voltmeters. Examples for voltages of everyday objects are given (e.g., batteries and power lines).
5. Electric Circuits	Looking at a circuit with one bulb, learners learn that "electric pressure differences" cause an electron flow just as air pressure differences cause an air flow and that the battery maintains a constant voltage.
6. Resistance	Electric resistance is introduced in analogy to a piece of fabric (e.g. a scarf) impeding an air flow and mathematically defined as $R = \frac{V}{I}$.
7. Parallel Circuits	Parallel circuits are used to make voltage rather than current the learners' primary concept when analysing circuits as well as to help them realise that a battery is a source of constant voltage (rather than constant current).
8. Series Circuits	Current and voltage in series circuits are explained using the concept of electric pressure.
9. Ohm's Law	At the end of the curriculum, learners' qualitative understanding of the relationship between voltage, resistance, and current is transferred to the equation $I = \frac{V}{R}$.
10. Practice and Extension Questions	The last unit aims to consolidate the learners' conceptual understanding of circuits using practice and extension questions.

Table 4.2: Units in "An Introduction to Electricity Using Potential Difference" as outlined in Burde et al. [2022].

The first unit introduces the concept that electricity can be used to move energy, and that this movement of energy acts in much the same way a bike chain is used to move energy from the pedals to rear wheel. Crucially, this draws an analogy between the electrons in the circuit, used to carry energy, and the links in the bike chain. The core point being that they are both not "used up", when going around their respective "circuits" but carry some unseen energy. A diagram illustrating this analogy from Burde's materials can be seen in Figure 4.1.

Unit two introduces the idea of airflow being the result of pressure difference between two areas that is mediated by any resistance between those two areas. This is introduced as trying to plug a hole with a piece of cloth. A small resistance made of a light material would make the air flow smaller and a big resistance would make it **much** smaller. The pressure in the different regions are shown by the density of dots, as in Figure 4.2.

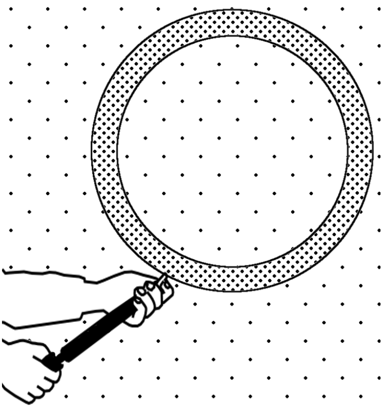

Figure 4.2: Higher pressure air inside a bike tyre, encoded using the density of dots from Burde and Weatherby [2021, p. 4].

The third unit draws the analogy of pressure to potential, teaching it as *electric pressure*. This *electric pressure* is high at the negative terminal, low at the positive terminal and changes throughout any wires "as soon as" they are attached. Unconnected wires have *normal electric pressure*. The encoding transitions from dots to colours in this unit, as is shown in Figure 4.3. The colour red denotes *high electric pressure*, blue *low electric pressure* and yellow *normal electric pressure*, not shown. Introducing the colour coding at this point allows learners to colour code the open circuits given in the exercises themselves.

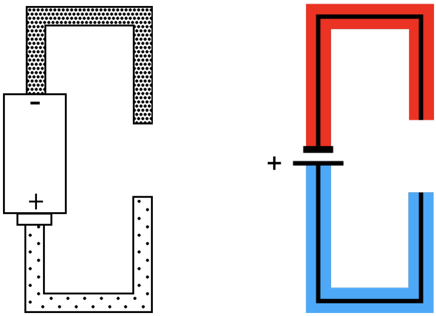

Figure 4.3: Moving from a dot based encoding of pressure, close to the idea of particle density, to a colour coding, easier for learners to encode themselves, from Burde and Weatherby [2021, p. 7]. The physicality and limits of this idea are discussed section 4.3.1.

The fourth unit moves from *electric pressure* (potential) being the central object of analysis to *electric pressure difference*, potential difference or voltage. Building on the colour coding of the last unit, it is now introduced that there are weak and strong *voltage sources*, in the form of batteries and the mains. It is also shown that this difference is measured with a *voltmeter* and its comparative nature is emphasised. In exercises, learners are asked to give voltages between points in open circuits both quantitatively and qualitatively.

The fifth unit now introduces the closed circuit, with the central learning outcome being that an *electric pressure difference* results in an electron flow, extending the air pressure analogy. Stronger *pressure differences* result in higher flows or currents and resistance is what regulates this. In this more content rich unit, learners acquire the qualitative relationship between *potential difference*, *current* and *resistance* as is shown in Figure 4.4. Current is the central property examined in this chapter with *ammeters* and currents "flowing together" at junctions also being discussed.

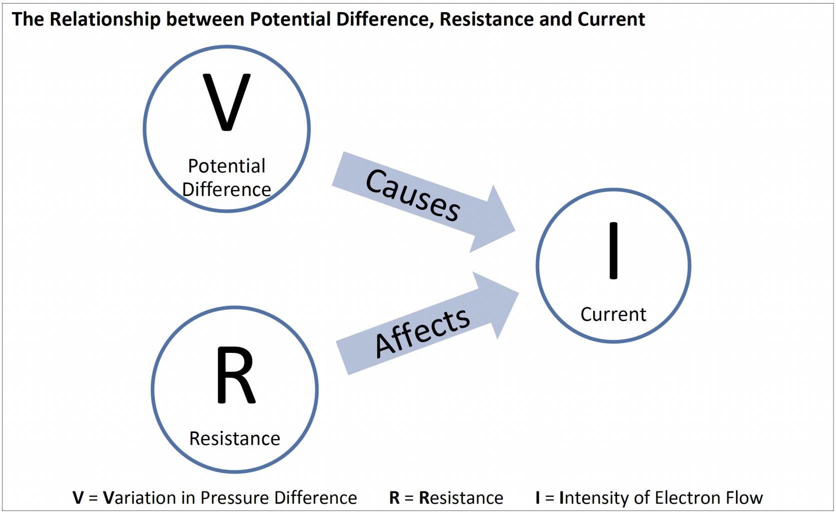

Figure 4.4: Diagram showing the qualitative relationships between the central physical properties in electric circuits, from Burde and Weatherby [2021, p. 14].

The sixth unit gives a microscopic account for resistance, separating materials into perfect conductors, conductors with resistance and insulators. It is also defined mathematically as $R = \frac{V}{I}$ and that this depends on the size and type of the material.

The seventh unit introduces the name parallel circuits formally for the first time and shows methods of identifying them and calculating their equivalent resistances. Learners focus on the fact that the potential difference is the same over all elements in a parallel circuit. These identical potential differences cause the current through each element, dependant on the resistance. These *partial currents* then flow together at the junctions and are provided by the battery.

The eighth unit introduces series circuits. Learners calculate equivalent resistances and how potential drops over resistances in series. An unusual addition here, compared with most schemes of work, is that a reason is given for how these potential drops come to be, using a model with intermediate states. In the intermediate state, the *electric pressure* has not yet changed in the wires and so must reach an equilibrium so that all the elements have the same current through them[319].

The ninth unit introduces Ohm's law quantitatively, but instead of introducing it as traditionally $V = IR$, the relationship is stated as $I = \frac{V}{R}$, emphasising the cause and effect direction of the relationship. The limits of the linearity of this relationship, to special, ohmic resistors, are made clear.

The final unit provides varied exercises allowing learners to consolidate what they have been taught in units one to nine.

4.2 *Theories Informing Instructional Design*

There are many theories that would and can inform instructional design. The ones mentioned in this section build upon fundamentals already discussed in Chapter 2. These theories and ideas are specifically useful when designing media for learners to interact with. It is of note here that when talking about media and, for that matter, technology, this does not presuppose digital or even new technology. The ideas presented here[320] are applicable to paper diagrams or even written language, as well as the tablet (iPad) application presented later.

[319] This is similar to the CASTLE Curriculum from Steinberg and Wainwright [1993], which will be discussed later.
[320] Although the ideas that informed the design and implementation of the materials under discussion here were established before its release, I would like to acknowledge the ideas presented in Wegerif and Major [2023] for providing clarity and structure to what were pre-existing decisions.

4.2.1 Tools and Their Use

In section 2.1.2 I introduced Vygotsky's idea of *psychological or cultural tools*. In this section we will examine how the external tool and its use results in changes in behaviour and thinking and how it is not possible to separate them entirely from their cultural and psychological dimension. The now ubiquitous example of Heidegger's Hammer[321] illustrates how the tool becomes an extension of the wielder. The wielder is no longer aware of its presence and now exists as a kind of wielder-plus-hammer system, engaged in a task. To wield the tool effectively, however, one needs practice. This is true even in cases where no active participation from the user is naïvely apparent, such as with a hearing aid[322]. Despite perhaps appearing passive the brain must adjust to processing a new type of input. Wegerif and Major [2023] give the example of a cane extending the senses of a blind person from Merleau-Ponty and Smith [2006] for a starker type of processing adjustment and sense extension. Winograd and Flores [1986] take these ideas and apply them to computers. Specifically, the means of computers to extend human abilities (to sense, do and think) and make what was not apparent, visible. Tools, from hammer, to computer simulation, to language, have the power to change the way we think and how we think will change the way we use them.

As we have seen in some of the arguments made by my learners in section 3.2.8 some tools can cause problems, i.e. learners showed *heuristics* that led them to incorrect answers. Tools that lead them to correct answers in certain situations, then did not work in others. To extend Heidegger's hammer metaphor, and quote Maslow [1966, p. 15-16], "it is tempting, if the only tool you have is a hammer, to see everything as a nail". One might extend this to apply beyond the case of it being the only tool, to case of the tool most "ready to hand"[323]. This underscores the importance, therefore, to equip our learners with

[321] Heidegger [1977]
[322] Brooks [1996]
[323] Part of Heidegger's idea of *Dasein* or perhaps in a *knowledge in pieces* perspective a *triggering probability*.

sufficient tools to deal with all situations that they might encounter and ensure that they can access them when required.

4.2.2 *Affordances and Constraints*

The *affordances* of a technology refer to what possibilities for action it or an aspect of it provides the user[324]. This can be as simple as a knee high surface *affording* sitting on or as complicated and mediated as language *affording* a new way to think or process information. The concept of the *affordance* lies in its use by a person and in how it affects that person, as Gibson [1979, p. 121] puts it, "an affordance is neither an objective property nor a subjective property; or it is both if you like. An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behavio[u]r." This mental-environment bidirectional relationship is underscored as essential, or as Wegerif and Major [2023, p. 45] put it simply, for Gibson the *affordance* is made up of "'material stuff' and 'mental stuff'".

Norman [1988], in contrast, is concerned with the design of tools, rather than the environment more broadly, and focusses on *perceived affordances*. That: 1) an object makes its function (a button to press, a dial to turn) understandable and 2) this action results in what a person expects to happen, forms the two complementary aspects of the *perceived affordance*. The example given by Wegerif and Major [2023, p. 43] to illustrate this is a computer mouse. The mouse can be moved and the buttons can be pressed, but the user expects this to correspond to a moving cursor on the screen, hence extending *perceived affordance*.

Constraints form the counterpart to *affordances* in that they are limits on possibilities for action. Although this may seem initially negative, the shrinking of this space of possibility can allow users to complete their task more easily. It is harder to find examples of *constraints* as they are not immediately visible. An example from my own work, a

[324] Gibson [1977]

circuit simulation I built for use in lower secondary, is that learners are *constrained* to using only 50Ω, 100Ω and 150Ω resistors. Despite lowering the space of possibility, it means that the ratio of the resistances will make the circuits easier to analyse. Note that although the examples here show helpful aspects of *affordances* and *constraints* that help with task completion, there are also unhelpful or even harmful examples of them.

To me, the positive aspects of both *affordances* and *constraints* are linked to the design of *scaffolding*[325]. The methods of scaffolding used in Wood et al. [1976] are summarised by Pea [2004, p. 432] as:

> "1. Channe[l]ling and focusing: Reducing the degrees of freedom for the task at hand by providing constraints that increase the likelihood of the learner's effective action; recruiting and focusing attention of the learner by marking relevant task features (in what is otherwise a complex stimulus field), with the result of maintaining directedness of the learner's activity toward task achievement. 2. Mode[l]ling: Mode[l]ling more advanced solutions to the task."

From *channelling* we can draw clear links to *constraints*, the word even appears in the description. The teacher or designer can avoid triggers for incorrect behaviour or ideas, placing *constraints* on the environment or tools available to the learners to direct their efforts fruitfully. *Focusing* is, in turn, directing learners to perceive (and engage with) certain *affordances* offered by the environment or tools in the learning situation.

4.2.3 Cognitive Load Theory

Cognitive load theory (CLT) posits that the human mind has a set amount of processing power and when doing a learning task this processing power is taken up by different types of *cognitive load*[326]. The theory divides the types of cognitive load into three: extrinsic (ECL), intrinsic (ICL) and germane (GCL). ECL is the (reducible) cognitive load that is due to the instructional materials. ICL is the cognitive load intrinsic to the task. GCL is the cognitive load caused by the creation of new

[325] As introduced on page 10. For a longer, teacher-friendly look at scaffolding, refer to Taber [2018a].
[326] Sweller [1988], van Merriënboer and Sweller [2005]

schemata, the kind of load to be maximised for learning. In essence, good instructional design minimises extrinsic load, by having simple, clear and intuitive to use materials that free the mental resources of the learner. Allowing them to focus on, firstly, completing the task and, secondly, learning from that task. Although I have explored these ideas most thoroughly in my other work (that does not appear in this dissertation[327]), these ideas prove foundational in providing a mechanism for the design principles discussed in the following section.

4.2.4 Representing Information In Physics Lessons

A *representation*[328] is a way of presenting information, be that by text, diagram or animation; interactive or not. We can regard a representation as a special class of tool. They are also special in the sense that they are ubiquitous and essential for teaching physics, whether equation, force diagram or spoken lecture. Building on this we can analyse them in terms of their *affordances* and *constraints*, but due to the multiple and parallel use of them in physics education, much research has been produced on their inclusion in teaching and learning materials[329]. Oft cited[330] and useful is the *cognitive theory of multimedia learning* (CTML). CTML has some basic assumptions:

A1. *The Dual-Channel Assumption*: Learners process audio and visual information along two (interacting) channels. [331]

A2. *The Limited Capacity Assumption*: Learners' processing of these inputs uses limited cognitive resources in each of these channels separately (assumption shared with CLT).

A3. *The Active Processing Assumption*: Learners actively select, organise and integrate incoming information into existing cognitive structures.[332]

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[327] Kapp et al. [2020, 2021], Weatherby et al. [2019, 2020, 2024]

[328] In this case (and throughout) a representation in the media sense, not an *internal representation* in a psychological sense.

[329] Treagust et al. [2017b]

[330] Mayer [2005] alone has 4820 citations at the time of writing (13/07/2024) according to Google Scholar.

[331] An idea originating from Paivio [1986].

[332] For a more detailed discussion of these assumptions, see Mayer [2005, p. 32-35].

This evolving theoretical base both builds upon and provides sets of principles to develop multimedia learning materials. As the evidence base evolves, principles get strengthened or called into question[333]. When developing the following materials I specifically concentrated on reducing *extraneous load*[334] using the following, well established[335] principles:

P1. *Coherence*: Remove any unnecessary information, other than what is essential for the key learning outcome. This is even if this information would appear to pique the interest of the learners. These can become *seductive details*, that distract from the learning outcomes.

P2. *Signalling*: Direct learners attention to the key information, organising principles or links between picture and text.

P3. *Redundancy*: Do not produce the same information in multiple forms that correspond to the same channel, taking up resources unnecessarily.

P4. *Spatial Contiguity*: Integrate words and graphics spacially to reduce the necessary searching for links between the representations and constant use of short term memory.

P5. *Temporal Contiguity*: Integrate words and graphics temporally to facilitate the establishment of links between the representations.

4.3 Adapting Existing Materials

Although Burde's materials improved learning outcomes in their language, country and school or classroom context, it is not to be assumed that adaptation into a new context is possible. To bridge this contextual gap, it is helpful to take the useful traits, as identified by Burde [2018] and translated in Section 4.1.1, explain using theory why they arise and contextualise them with other results, considering how to adjust them to the context at hand. In this section, I integrate these insights and theory from the previous two chapters, as well as discuss how the

333 Feldon et al. [2021]
334 Fiorella and Mayer [2021]
335 Mayer [2024, p. 15]

materials were specifically redesigned to fit their new context of British comprehensive schools, using concrete examples from the materials produced.

4.3.1 Sequencing and Content

An initial, normative check is whether the course is inline with the National Curriculum for England at Key Stage 3 (KS3). As shown in Table 4.3 the course includes all topics required at KS3, with the exception of potential difference with regards to bulb ratings. This omission is justifiable in my eyes, as its inclusion may serve to strengthen the misconception that *electricity*† *is required*, in this case that voltage is required. Although light bulbs are in practice matched to the voltages that they are designed for, they can be used in circuits for which the voltage does not match - resulting in a difference in the brightness of the bulb. Of course, if they are too far mismatched they may not light at all or "burn out". Understanding this completely requires a developed concept of the relationship between resistance, current and voltage, that is a final goal of the course[336]. In other words, that a light bulb is developed to have a certain resistance at a given voltage that results in a given current, an analogue to brightness. With this level of intricacy and the risk of reinforcing *alternative conceptions*, it is reasonable to omit at KS3.

Now we have established that the norms of the National Curriculum are met, I change focus to look at content structure for effective attainment of conceptual knowledge. Burde's first insight, introducing *potential* and *potential difference* before *current*, in opposition to commonly used text books[337] is done to stop the idea of current from dominating reasoning[338]. Put more technically, reasoning with current will become the dominant heuristic for solving problems. This builds upon the

[336] The nature of a light bulb's resistance with voltage is not a learning outcome at KS3. Meaning that knowing about bulb ratings could, at worst, be regarded as essentially a rote learning requirement unattached from the concept of voltage.
[337] Locke et al. [2022]
[338] von Rhöneck [1986a, p. 87]

National Curriculum for England	Lesson Number
Current electricity - KS3 [Department for Education, 2014, p. 66]	
electric current, measured in amperes, in circuits,	Chapter 5
series...	Chapters 7 & 8
... and parallel circuits,	(used throughout)
currents add where branches meet and current as flow of charge	Chapter 5
potential difference, measured in volts,	Chapter 4
... battery	Chapter 5
... and bulb ratings	-
resistance, measured in ohms, as the ratio of potential difference (p.d.) to current	Chapter 6
differences in resistance between conducting and insulating components (quantitative).	Chapter 6
Electricity - KS4 [Department for Education, 2014, p. 78 - 79]	
measuring resistance using p.d. and current measurements	Chapter 9
exploring current, resistance and voltage relationships for different circuit elements,	Chapter 5
...including their graphical representations	-
quantity of charge flowing as the product of current and time	Chapter 5
drawing circuit diagrams;	Chapter 1
exploring equivalent resistance for resistors in series	Chapter 8
the domestic a.c. supply; live, neutral and earth mains wires;	Chapter 4
... safety measures	Chapters 6 & 7
power transfer related to p.d. and current, or current and resistance.	Chapter 7

Table 4.3: National Curriculum for England Content Outline for Circuit Electricity from Department for Education [2014].

ideas of tool use introduced in Section 4.2.1. If the "tool to hand" is potential, then it is less likely learners will result to *arguing from current*, preventing them from slipping into a range of argument patterns that produce *alternative conceptions*. There is also a physical-logical reason to do this, although the *potential difference* is caused by charge imbalance, the causal relationship between *potential* and *current* is that a *potential difference* causes a charge flow i.e. a *current*. The argument must therefore begin with *potential*, making it a logical starting point. For circuits more complicated than a simple loop, the algorithm for determining the behaviour of the circuit begins with determining *potentials*[339]. To introduce *potential* at all seems rare in KS3 text books[340]. The idea of *potential* is foundational for *potential difference* and its often exclusion feels like an oversight, due to the fact it is not a final learning outcome as listed in curriculum plans. *Potential difference* is often seen as causing the most problems to learners[341]. Illustrated by the fact that relatively few lower secondary learners, even in the 'academic' stream of a comprehensive school, had the "Idea of same voltage across two circuits in parallel", i.e. 20% of 13 to 14 year olds and 40% of those in their final year of mandatory education[342]. Building in *potential* as a crucial and often lacking foundation for the idea of *potential difference*, as *electric pressure* and *electric pressure difference* may prove a mechanism for a successful intervention, by promoting the understanding of a *comparative nature of voltage*[343].

Ohm's Law, the linear relationship between current and voltage for ohmic resistors[344], is introduced quite late in order to try and avoid the tendency to use the definition instead of build an understanding of the underlying concepts[345]. Teaching *voltage* and *current* separately and not reducing the definition of *voltage* to $V = IR$ is done by introducing

339 Discussed in the next section.
340 Locke et al. [2022], Robbins et al. [2024]
341 Maichle [1979], Jung [1979]
342 Johnstone and Mughol [1978, p. 49]
343 Insight 4 from Section 4.1.1.
344 A special class of resistors whose resistance is independent of current.
345 Muckenfuß [1980, p. 35]

examples where *potential differences* do not result in a *current* i.e. open circuits[346]. This provides us with another opportunity to centre *potential difference* and introduce it first and to present a wide array of circuits and allow learners to develop *span* for what a *closed circuit* actually is. Delaying the introduction of Ohm's law also allows learners to get comfortable with reasoning qualitatively about the relationships between *potential difference*, *current* and *resistance*[347], as learners cannot refer to a mathematical definition and *refuse to reason qualitatively*.

As the course is about developing this qualitative understanding, providing learners with a sense of mechanism[348] for these is important. Without having this sense of mechanism it could lead learners to fall back on unhelpful reasoning or be unconvinced by our model. Burde [2018] also says offering a microscopic model helps satisfy learners' epistemological curiosity[349] - i.e. allows us to answer the "why" and not just the "what" version of what is happening. This comes with the counter point of avoiding things that do not contribute to an understanding of a qualitative model of the relationships. This includes anything that shows the limits[350] of the model as well[351]. This necessity for conciseness is perhaps even more pronounced in the UK, where teachers have comparably little autonomy over the content they teach, where German teachers are able to exercise more control. Therefore, it is important to ensure that the content is tightly inline with the National Curriculum and to avoid content that does not meet those learning outcomes[352].

[346] Insight 9 from Section 4.1.1.
[347] Insight 5 from Section 4.1.1.
[348] A sense of mechanism is how a *p-prim* is defined after all!
[349] Insight 8 from Section 4.1.1.
[350] Discussed in Section 4.3.2.
[351] Insight 11 from Section 4.1.1.
[352] This is not an endorsement of either system.

4.3.2 *Physicality and Limits of the Model*

A physical model of the relational phenomena in direct electric circuits is governed by small differences in electron surface density, i.e. charge separation that results in potential differences[353]. Unlike the model used here that suggests that the conduction electron density varies strongly throughout the circuit, it is only these surface electrons that vary at a very low ratio. We allow ourselves this *idealisation*,[354] or simplification, so as not to unnecessarily add complexity to the model that is not useful in achieving the learning goal of understanding the relationships present between current, potential difference and resistance. However, in the spirit of "intellectual honesty"[355] learners are provided with this information in a simplified form in the textbook, despite it not being a learning goal of any lesson.

The model also ignores the effect capacitance has on electron surface density in open circuits, as well as the variation in electron surface density that is due to wires not being resistance free. These, however, are due to more standard assumptions present is many school curricula.

4.3.3 *Analogy and Presentation*

Introducing the idea of electric *potential* using the analogy to air pressure as *electric pressure*[356] was shown to be effective by Burde [2018] and is also a part of another successful intervention[357], The CASTLE Curriculum[358]. The CASTLE Curriculum makes extensive use of capacitors[359] making it (among other reasons) inappropriate for lower secondary comprehensive schools, but illustrates the possibility of a similar method working in the English language. Both build on the

[353] Chabay and Sherwood [2018]
[354] For a discussion of this idea see Winkelmann [2023].
[355] A phrase frequently used by Bruner [1977] and, in my opinion, also of central importance when constructing curricula.
[356] Insight 2 from Section 4.1.1.
[357] Brown [1992] in Wainwright [2007]
[358] Steinberg and Wainwright [1993], Steinberg [2016]
[359] Burde [2018] contained these to a lesser amount and the topic was removed in subsequent materials.

familiar, *source domain* knowledge of air pressure phenomena, i.e. air leaking out of a bike tyre or lilo, and begins to develop the understanding of phenomena in the *target domain*, electric circuits. The important thing about the *source domain* here is that a good understanding of pressure or fluid dynamics is not essential for establishing the necessary isomorphism between the domains, building on theory discussed on page 18, allowing for an understanding built on every phenomena alone.

The previous two insights place potential as the key physical constant for analysing electrical circuits. There are multiple ways of visualising the key physical constants in simple electric circuits[360]. This visualisation allows us to go beyond one of the failings of other pressure models, such as the water circuit model, which contains no visible pressure difference[361]. As we wish to impart an understanding of *potential* and *current*, special care is shown for how to portray them.

Encoding potential through height, although it builds well on the *p-prim* "released objects fall"[362], requires what Burde [2018] refers to as "ability for abstraction"[363]. This additional difficulty, induced by an increased demand in spatial reasoning, can be assessed through the lens of *Cognitive Load Theory*. The transformation of a two-dimensional circuit diagram, through both rotation and addition of a third dimension representing a height displaying the potential, presents an additional *cognitive load*[364]. This can be reduced in that a computer simulation can take over these transformations for the learner[365], shown in Figure 4.5 (left), but this means that learners' access to using this encoding themselves as a tool for learning is made more difficult. In contrast, the colour encoding requires no geometric transformation of the two-dimensional circuit diagram, shown in Figure 4.5 (right), and a colour

[360] Weatherby et al. [2019], Burde et al. [2021]
[361] Muckenfuß [1980, p. 36]
[362] diSessa [1993]
[363] Original German: Abstraktionsvermögen
[364] Pillay [1994]
[365] An argument I made in German in Weatherby et al. [2019].

scheme using red and blue pencils or crayons can be accessed by the learners easily as the basis for qualitative analysis of the potentials[366]. This encoding is colour-blind friendly and builds upon known cultural norms such as the high-low temperature scale being marked red-blue on a bathroom tap.

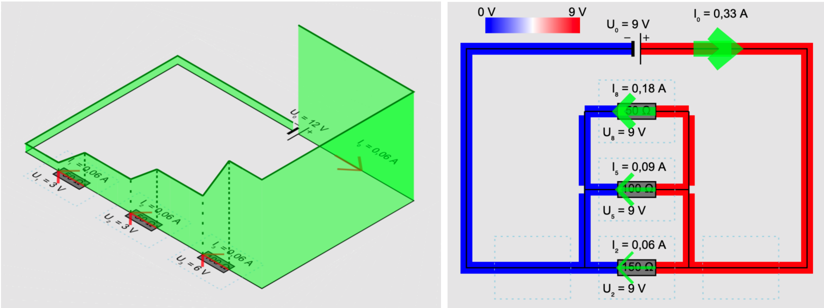


Figure 4.5: Simulation showing height and colour encodings of potential as well as current encoded as the width of arrows. Simulation author's own work, accessible at https://thomas-weatherby.com/simulation_en.html. Previously published in Wilhelm et al. [2021].

How the current is encoded, i.e. whether moving charge packets are included, can be dependent on the learning goals at hand. For example, if the goal is to address the *current use* conception it may arguably be advantageous to encode the charge moving around the circuit, to show it has not been lost[367]. However, this advantage is only present in a dynamic/moving visualisation. It can also be argued that visualising these "charge packets", such as in Figure 4.6, may trigger learners to argue from current[368]. These "charge packets" can act as *seductive details*. As a known misconception is *arguing from current*, directing attention to moving charges, using this visualisation, may trigger argumentation along these lines. This acts especially counter to the aim of the scheme of work to encourage reasoning from potential. "Charge packets" also add visual noise to static drawings and it is time consuming for learners

[366] Insight 3 from Section 4.1.1.
[367] Burde et al. [2021]
[368] A tendency seen in Cohen et al. [1983].

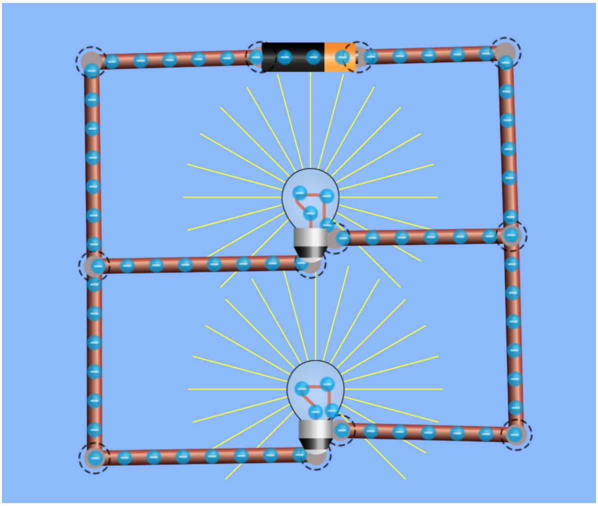


Figure 4.6: Screenshot from PhET "Circuit Construction Kit: DC" showing moving "charge packets". Simulation by PhET Interactive Simulations, University of Colorado Boulder, licensed under CC-BY-4.0 (https://phet.colorado.edu).

to draw these on their diagrams, instead current is portrayed using arrows. This also has the advantage that learners are able to encode information in the same way as their learning materials, establishing a consistent representation, enabling mastery of it as a *cultural tool*.

Again, in order provide learners with a potential-centred reasoning, they are instructed with an algorithm with which to analyse electric circuits using *electric pressure differences*. Learners colour *high* and *low electric pressure* from the voltage source. They then can search the circuit for *electric pressure differences*, i.e. voltages over resistors, where there must be a current. It is important at this point that there is an introduction of *pressure difference*. In EG2 this is done as an explicit learning outcome that a *current* requires two things: 1) an *electric pressure difference* and 2) a path between those places. This is done to avoid wishing to imply/reinforce the *alternative conception* that "no pressure implies no flow"[369], especially when there is a region with *neutral electric pressure*. This is argued on the basis that current has to be provided by the voltage source, avoiding discussing current "splitting" at junctions in parallel circuits, triggering *battery provides a constant current*, *local argumentation* and *sequential reasoning alternative conceptions*[370]. This algorithm is learnt as *procedural knowledge*. It provides a key positive *constraint* in that learners are directed away from argumentation from current, as stated in insight 1. In this case, the algorithm and argument structure both offer *constraint* and *scaffolding* from which the learners are more likely to avoid unscientific reasoning, enabling the learner to solve previously unanswerable problems. Furthermore, having a well structured and declarative set of instructions, provides a clear and practicable learning goal.

The epiSTEMe project, also teaching electric circuits and conducted with the same target demographic as in this intervention, used a wide range of models, resulting in no learning gain[371], although some of the stated aims of the project go beyond purely improving educational attainment[372]. From this, I hypothesise that the inclusion of only two models, the bike chain and electron gas model, is a factor in the success of Burde [2018]. Although I do not believe that the use of only two models is enough to "promote the reflective use of models"[373], a reduced number allows for more practice with each individual model, enabling the learner to become well-versed with using them, as well as complementary learning outcomes that can address specific *alternative conceptions* that the other model leaves unaddressed. This seems to be a plausible mechanism for improving learning outcomes in this case. Related suggestions of the twin use of water circuit under pressure and bike chain model are, however, not new[374], but as stated above, are not often implemented.

369 Kaufman et al. [1992] in Chi et al. [1994a]
370 Insight 7 from Section 4.1.1.
371 Ruthven et al. [2017]
372 Ruthven et al. [2010], Taber [2012], Taber et al. [2018]
373 Insight 10 from Section 4.1.1.
374 Closset [1984b, p. 29]

Bridging Vocabulary	Scientific Vocabulary
Electric pressure	Electric potential
Electric pressure difference	Potential Difference/Voltage
Intensity of electron flow	Current
Resistance	Resistance

Table 4.4: Table showing bridging vocabulary to the scientific vocabulary. Bridging vocabulary is used together with scientific vocabulary in early chapters and then scientific vocabulary is used alone in later chapters.

Developing materials on the basis of alternative conceptions has lead to increasing learning outcomes[375]. in addition to the strategic inclusion and preclusion of topics and visualisations, it is possible to structure phrasing and vocabulary in a way is conducive to scientific reasoning and avoids strengthening *alternative conceptions*[376]. This is done on the basis of analogies to the everyday experiences of the learner, among others. This set of bridging vocabulary can be seen in Table 4.4. The vocabulary is chosen to have good links both to the source domain, but also the scientific vocabulary that will be used later. The fact that potential and pressure both start with a 'p' is helpful, for example, and not the case in the original German with "Potential" and "Druck". Also, that current is called "intensity of the electron flow" provides an immediate link to explain why its formula symbol is I. These needed adaptation, of course, from German.

The first of two other specific examples of key definitions are that of current, Muckenfuß [1980, p. 33] suggests avoiding the tautology "a current flows" and instead opting for "a current/flow is created"[377] to avoid current being seen as a quasi-material. I, instead, opt for something with an even higher level of specificity "electrons flow, we call this a current". The second of these are regarding the mechanism

[375] Maichle [1979], Burde [2018], Wilhelm [2005]
[376] Insight 6 from Section 4.1.1.
[377] German original: Es entsteht eine Strömung

for potential difference being distributed by resistance over resistors in series. This is done as in the CASTLE Curriculum through intermediary states, which are called initial, transit and steady in their course intended for ages 16-plus. This was thought unsuitable for KS3 and called starting, changing and final respectively, to make the ideas more accessible.

4.3.4 Reading Age Metrics and Readability

Whilst recruiting for the study, a teacher raised a concern that their students may struggle with the complexity of text in "An Introduction to Electric Circuits". The text was initially conceived to be used in German "Gymnasium", a school equivalent to the British "Grammar school", preparing learners for a university education. Pupils attaining the "allgemeine Hochschulreife", i.e completing this form of schooling, accounted for 34.5% of the pupils in 2019[378]. This is in stark contrast to the 95.4% of pupils in England who are in mainstream state-funded secondary schools[379] (i.e. excluding special and alternative provision schools) who are our target audience.

There are multiple measures for reading age used in the literature, here I use the *Flesch-Kincaid Grade Score*[380], which I convert into age for ease. This score was developed to assess comprehensibility of technical manuals for the US Navy[381], so although not a perfect analogue, as both texts are technical in nature, it is better than a wider comprehensibility metric. The formula to calculate the scores were determined by using only the comprehension tasks of the Gates-MacGinitie Reading Tests[382] to assign each of the service personnel a "Grade Level". The service personnel then completed a series of comprehension tasks on technical manuals. A linear regression was then carried out to find the constants in the following equation that correspond to 50% of the service personnel with a

[378] Hessisches Statistisches Landesamt [2020]
[379] Department for Education [2024]
[380] This gives a "grade level" inline with the American school system.
[381] Kincaid et al. [1975]
[382] Gates and MacGinitie [1964]

given "grade level" scoring 35% on *cloze*[383] comprehension tests under test conditions. If we look at this using a CLT lens, if the learner is using their mental capacity to answer a mere 35% of the answers correctly[384], there are little cognitive resources left for construction of new schemata. This implies that it would be desirable to have a Flesch-Kincaid score significantly below that of the reading age of the target audience. To calculate this score, the *Flesch-Kincaid formula* is used:

$$\text{“Reading Age”} = 0.39\frac{\text{Number of Words}}{\text{Number of Sentences}} + 11.8\frac{\text{Number of Syllables}}{\text{Number of Words}} - 10.59$$

I would like at this stage to make clear that this is not an ideal method to compute text complexity, but it is a well trodden path. In the time since the development of most reading metrics, computer linguistics, natural language processing and artificial intelligence have developed as fields of study. In these fields there have been strides made in the classification of text difficulty[385], with modern models significantly outperforming, but still correlating with, Flesch-Kincaid[386].

Using this formula I carried out a reading age analysis on the intially translated text. Getting the syllable counts from the Carnegie Mellon Pronouncing Dictionary, via the python library `cmudict`[387]. The *Flesch-Kincaid Reading Ages* for each of the chapters can be seen in Figure 4.7 and are unsatisfactorily high for all chapters for our target audience, year 8, aged 12-13. A full rewrite was carried out, using the principles in Klare [2000, p. 18-20]. This resulted in reducing the complexity to significantly below the target age of the learners, as shown in orange. Using the *affordances* of digital displays, learners could also be shown additional information as *hover over text*. This is particularly prevalent in "An Introduction to Electric Circuits" as scientific vocabulary is shown next to *bridging vocabulary* in brackets - i.e. electric pressure (potential).

383 Otherwise know as "fill the gaps".
384 The answering of *cloze* questions presents a cognitive load too, of course.
385 François [2015]
386 Crossley et al. [2019]
387 Day

This reduces the reading age of the texts further to the values shown in green.

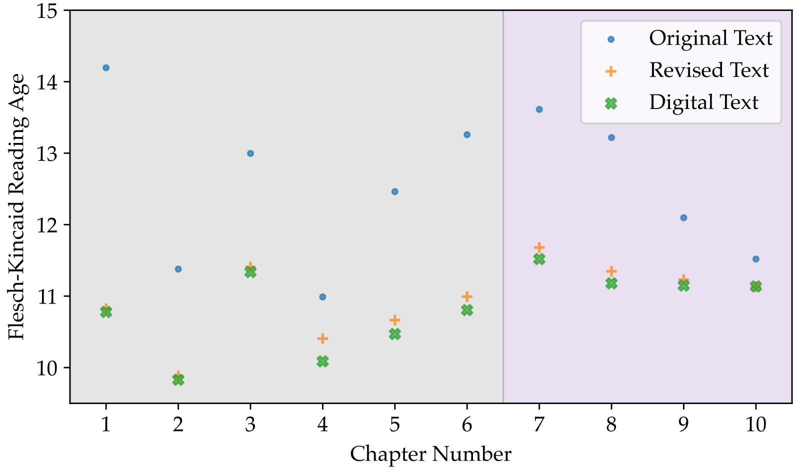


Figure 4.7: Reading ages in three different versions of "An Introduction to Electric Circuits". The blue dots show the original translation, orange pluses a modified version to improve readability and green crosses a computerised version where extra information is shown as "hover over" text. The grey and lilac shaded areas show chapters including Key Stage 3 and 4 learning objectives respectively.

This new text, with significantly reduced reading age, was used as part of the materials in the intervention carried out in the first year.

4.3.5 *Vocabulary and Word Frequency*

The same teacher, from Section 4.3.4 asked whether I had considered what "tier" the vocabulary was in the textbook. This idea refers to dividing vocabulary into three tiers, as shown in Figure 4.8. Tier 1 includes words used in everyday conversation which should be familiar to learners. Tier 2 includes vocabulary which, although advanced, has uses across multiple school subjects and maybe familiar from previous topics or other lessons. Tier 3 are subject specific words that will need to be introduced and defined in lessons on the topic and although possibly familiar from other contexts, will need to either be learned or re-contextualised.[388][389] This model, although perhaps valuable for interpreting the teaching of specific vocabulary ad hoc, the assignment of a given word to a "tier" is not easily automatable, so another method needs to be found. A good analogue for these tiers would be the frequency of occurrence of a given word.

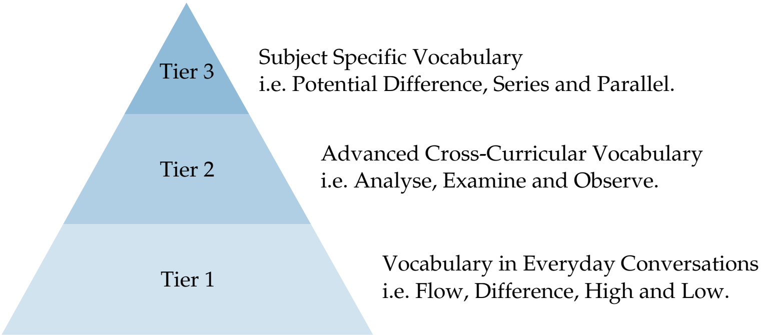


Figure 4.8: Classification of words using a tiered model of vocabulary after McKeown and Curtis [1987].

To ensure the text is readable for learners of all ability groups at lower secondary an analysis of the occurrence frequency of the words in "An Introduction to Electric Circuits" was carried out. At this point it may be useful to define some words not in common use in wider educational research, but useful when discussing this topic.

Dictionary word, lexeme and lemma form a set of ideas that will be treated as one in the following analysis. It is, however, good to be aware of certain subtleties in differences between possible usages. "A dictionary word" or lemma is the form of a word or phrase as given in a dictionary. Important to note is despite "word" being used in the singular, these can take forms of idiomatic phrases. An example of which, the game "twenty questions", does not have derivable meaning

[388] McKeown and Curtis [1987, p. 155]
[389] Beck et al. [2013]

for someone familiar with the constituent words. Lemmatisation is the act of transforming any word into a lemma. A lexeme is the meaning unit ascribed to one of these lemmata.

A morpheme is the smallest meaning unit in a language. The best way to get an insight into the meaning is with an example. "Unbreakable" is constructed from three morphemes: "Un-" meaning "not", "-break-" the root and "-able" meaning "can be done". These are important as it provides us with ways of thinking about which words might be *potentially knowable* with some *morphological problem solving*[390].

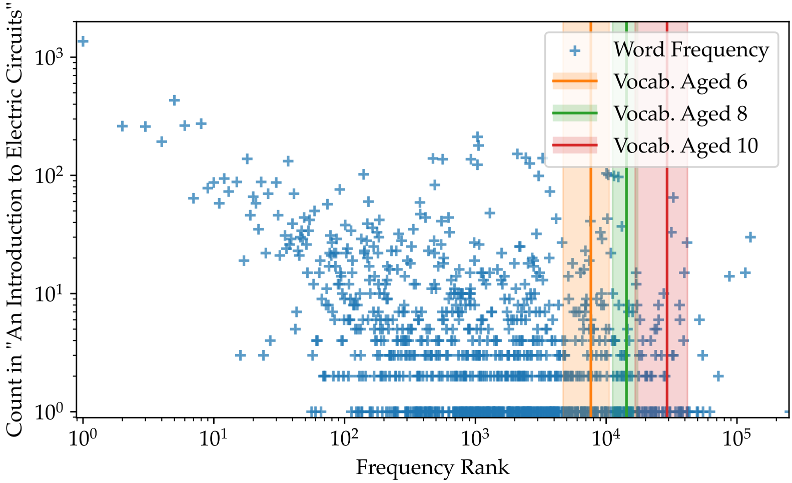


Figure 4.9: Frequencies of words occurring in "An Introduction to Electric Circuits". Coloured lines show the estimated vocabularies of learners aged 6, 8 and 10 respectively, corresponding to U.S. Grades 1, 3 and 5, as measured in Anglin, 1993. Shaded areas represent one standard deviation from the mean.

The text was split at spaces into whitespace-less strings and each occurrence of that string was counted. This ignores a class of dictionary words, compound phrases that contain spaces. The frequency rank

[390] Anglin et al. [1993]

words were then looked up using the `wordfreq`[391] package for Python, that looks up word frequencies for unlemmatised data. The `wordfreq` package uses a range of sources including books and internet comments. This ensures that the sample presents a representative sample of words[392]. The results of this data are seen as the blue crosses in Figure 4.9.

	Grade 1		Grade 3		Grade 5	
Word Type	Estimate	SD	Estimate	SD	Estimate	SD
Root Words (1)	3,092		4,582		7,532	
Inflected Words (1)	2,753		4,135		5,595	
Derived Words (1)	1,794		5,577		16,088	
Literal Compounds (1+)	2,610		4,451		8,312	
Idioms (2+)	149		667		2,467	
Total	10,398	2,961	19,412	3,092	39,994	12,638
Single Word (Lower Bound)	7,639		14,294		29,215	

Table 4.5: Estimated Vocabularies of School Children in the USA. (1) Denotes purely one "word" entries, (1+) is a mixture of single and multi-"word" entries and (2+) shows purely multi-"word" entries. Table modified from Anglin et al. [1993].

To contextualise these results, vocabulary estimates for U.S. 5th graders (aged 10 or 11) were taken from Anglin et al. [1993]. These learners provide us with a good estimate for entrants to British secondary schools. Anglin uses an unabridged dictionary containing inflected and derived words, just as the `wordfreq` package does. However, some of Anglin's dictionary entries are (both space separated and single word) literal compounds and idioms. As we are interested in getting a lower bound, we can discount the contribution of vocabulary from these literal compounds and idioms. The single word lower bounds are calculated as shown in Table 4.5 and displayed graphically in Figure 4.9. The standard deviation for the whole sample as scaling would assume equal contributions from each word type, as Anglin et al. does not provide breakdowns of these. The full standard deviation is used in order to obtain a more reliable lower bound for expected vocabulary at 16,577

391 Speer et al. [2018]
392 Nation and Waring [1997, p. 18]

words for a learner one standard deviation below the mean, entering secondary school. This should encompass more than 83% of the total learners. This lower bound was used to generate a list of words to be featured in a vocabulary list for use alongside the text. Reasoning for inclusion (or not) in the vocabulary list can be seen in Appendix B.1 and is based on the ideas of vocabulary tiers discussed earlier. Using this list, a handout (contained within the Booklet linked in Section 4.5) was produced explaining the meaning of the words both pictorially and in simple English. The code for doing this can be used and run by teachers using this python app.

Figure 4.10: QR Code for the vocabulary list generator.

This "dictionary method" is judged in later literature to not be a reliable measure of vocabulary (c.f. Coxhead et al. [2015], Biemiller and Slonim [2001]), with researchers conducting root-word vocabulary tests, to estimate root-word knowledge and hence account for *semantic reasoning*. This would change the methodology of the tagging needed. However, considering this is a preliminary step to highlight problematic vocabulary, and only used in the context of an overly generous lower bound, this rougher, less computationally intensive method is likely sufficient.

4.3.6 *Inclusivity*

Aside from all the measures taken with regards to linguistic accessibility there were other accessibility considerations made. Names used were taken from across genders and cultural backgrounds, reflecting the makeup of the UK. With the emphasis on visualisation, special attention was paid to whether the resources were accessible to those with sight impairments, and so texts were produced at high contrast, tested using the University of Utah's WebAIM platform. All colour-schemes were suitable for people with all main forms of colour-blindness, excluding achromatopsia (complete colour-blindness)[393], which is incredibly rare affecting only 1 in 30,000 people[394]. This was tested using the Coblis Colo(u)r Blindness Simulator[395].

4.3.7 *The Resulting Materials*

All resulting materials (a text book, slides, a teaching guide and worksheets) were provided to teachers and learners. These formed the basis of experimental group 1 (EG1). The materials and a brief teacher-friendly explainer can be found here. The resource pack is a locked zip file the password to which can be obtained by emailing me at weatherby@physik.uni-frankfurt.de.

Figure 4.11: QR Code for the book and resource pack used for experimental group 1.

[393] Gordon [1998]
[394] Tsang and Sharma [2018]
[395] Wickline [2001]

4.4 *Collaborative Task Design and the Affordances of Digital Teaching*

There are lots of types of collaborative tasks that take place in the physics classroom, whether that be during practical work, where material constraints or the manual complexity of the task necessitate two or more learners working to complete a common task or even in short teacher-learner discussions where the teacher may provide spoken scaffolding to structure a learner's answer. This section examines why a teacher might choose to design tasks collaboratively and how that is achieved successfully, as well as, the *affordances* digital tools offer for collaboration within the classroom.

4.4.1 *Learning Gains from Collaborative Teaching and Learning Practices*

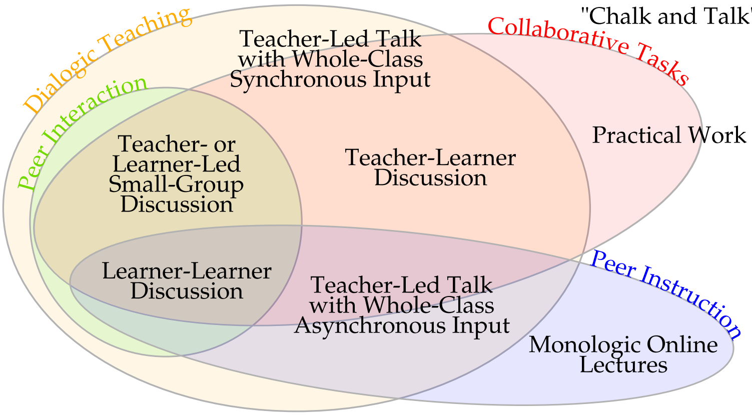


Figure 4.12: Intersecting Task Types related to Dialogic Teaching, Peer Interaction, Collaborative Tasks and Peer Instruction, with concrete tasks that are included (partially in these approaches).

In the spirit of education as a "design science"[396], all the principles and theories need to produce desired outcomes and the transferability needs to be justified and motivated for the context under investigation, lower secondary school science. The following section outlines the

[396] Sharples [2009], Laurillard [2012] in Wegerif and Major [2023]

motivation to develop an intervention on this basis, looking at a range of age groups. A "collaborative task" in the (science) classroom can take multiple forms. Common and overlapping terminology is shown in Figure 4.12. However, in short, what is meant here by a "collaborative task" is a group of learners with a common goal, using talk as their main method of communication.

A 2017 report issued by the Educational Endowment Foundation showed the efficacy of using dialogic teaching across the curriculum in a large-scale, comparative study of year 5 classes ($n_{\text{Classes Treatment}} = 38$)[397], in which learners made significant learning gains across the three "core subjects" of English, Maths and Science. Similarly, interventions in higher education, found that implementing peer instruction[398] increased scientific concept knowledge acquisition when compared with traditional lecture-based teaching. Furthermore, in a recent meta-analysis, peer interaction interventions with secondary school learners were shown to have an effect strength on the upper end of medium ($g_{\text{Hedge}} = 0.62$)[399]. These effects, however, seem more difficult to reproduce in our specific setting, lower secondary introduction to electricity, with no significant learning gains being found in the epiSTEMe project[400]. However, with this intervention being ten years in the past (2010-11) and purely analogue, there is promise of building on the approach, integrating successful ideas from this research as well as that conducted by the co-authors[401] on the use of simulations in school science. There is strong evidence that integrating this kind of task design is beneficial for learning outcomes. Understanding the features of a successful intervention of this kind should enable the fruitful integration of it in our setting.

[397] Jay et al. [2017]
[398] Crouch and Mazur [2001], Karabulut-Ilgu et al. [2018]
[399] Tenenbaum et al. [2019]
[400] Ruthven et al. [2017]
[401] Howe et al. [2013]

4.4.2 *Collaborative Task Design*

Through a literature review, Heeg et al. [2020] establish seven features of fruitful collaborative task design, which we can use to analyse the features of current technology and highlight the need for an additional tool to scaffold the learning process. The features are listed below, as they appear in Heeg et al. [2020], with a design requirement given at the end of each paragraph, based upon previous work in Weatherby et al. [2022].

In contrast to using a "digital improvable object"[402] as the basis of collaborative tasks, as in group work using Interactive Whiteboards[403] or other interactive computer programmes[404], the features outlined below are used to make an application that necessitates a tight structure. The hope here is to build on the successes of the interventions outlined in the previous section without the cross curricular designs and extensive support through "training, handbooks, video, and regular review meetings with peer mentors"[405].

FEATURE ONE (F1): BECOMING AWARE OF ONE'S OWN CONCEPTIONS
Learners who have completed a clarifying task before a discussion task, i.e. a mind-mapping task[406] or answering the discussion question individually[407], seem to perform better in the collaborative task. Hence, the design requirement to *enable individual reflection*.

FEATURE TWO (F2): EXTERNALISING INDIVIDUAL IDEAS
Ensuring that learners externalise their own ideas serves dual purpose: it necessitates learners access and organise their conceptions to speak them aloud and provides a point of comparison for an interlocutor. Heeg et al. [2020] examines this narrowly in the context of drawing as a task in the chemistry classroom, but we can broaden the scope. By externalising their own ideas, learners must reflect on them and

[402] Twiner [2011], Twiner et al. [2014] in Littleton and Mercer [2013b]
[403] Mercer et al. [2010]
[404] Mercer et al. [2004]
[405] Jay et al. [2017, p. 44]
[406] van Boxtel et al. [2000]
[407] Olsen et al. [2019]

also reflect on how to communicate them, engaging with the *cultural tools* with which the ideas are represented[408]. Reworking their *internal representation* to an *external* one, learners are given an opportunity to rework and reshape their thoughts. Having created the *external representation*, this can then serve as a discussion object and a point of comparison. These objects form a basis that then can be reworked with the interlocutor and then re-internalised (F5). Having the question on a tablet in your hand (as opposed to on a board at the front) *affords* gesturing to text and image, facilitating *externalisation* in a different way, easily shareable in small groups. Hence, the design requirement to *necessitate engagement though externalisation*.

FEATURE THREE (F3): INITIATING COMPARABLE SITUATION MODELS
As outlined in Section 2.1.6, learners' conceptions are triggered differently by the current situation. Therefore, in order that there can be a meaningful discussion, there needs to be some common representational forms and background knowledge established, referred to as the *situation model*[409]. For our learners, this means being able to interpret any diagrams and vocabulary in the questions, achieved by setting questions that have been modelled, at least partially, in preceding sections of the lesson or activating things from the wider scheme of work and reinforcing long term recall. Hence, the design requirement for *embedding in a comprehensible context*.

FEATURE FOUR (F4): ENSURE ACTIVE INVOLVEMENT FOR ALL
This kind of classroom discussion may be new for the learners, hence they may require instruction on how to conduct it. There are multiple techniques that can be employed to ensuring learners have clearly defined roles, or in this case, a list of sub-tasks. This can be be compared to a wider way of scaffolding called *collaboration scripts*[410]. Hence, the design requirement to *scaffold involvement for all*.

FEATURE FIVE (F5): OFFERING EACH LEARNER OPPORTUNITIES TO REFLECT ON EACH OTHER'S CONCEPTUAL UNDERSTANDING
This involvement should also be productive and facilitate engagement

[408] For some basis to these ideas refer to Section 2.1.2
[409] Kintsch and van Dijk [1978] in Glaser [1991]
[410] Kollar et al. [2006]

with ideas from all interlocutors. Building on the shared *situation model* learners must integrate the differences in their thinking into a shared, convergent viewpoint[411]. The starting point for this (unless complete transferral is done from one learner's conception to the other) would be both of the learners understanding each other's initial conception, again a way of establishing a common basis for discussion. Hence, the design requirement to *focus the learners on productive active engagement in talking and listening*.

FEATURE SIX (F6): INTEGRATING DECISION-MAKING PROCESSES

The learning goal in a science classroom is to adopt the scientific explanation. Therefore, the direction of travel is predefined towards consensus. Reaching an agreed upon answer as a group is one of the "Ground Rules for Exploratory Talk" from Mercer et al. [1999], which have produced encouraging results for increasing problem solving competencies and learning outcomes in a wide range of studies[412]. Hence, the design requirement, at least in science subjects, to *lead towards consensus*.

FEATURE SEVEN (F7): OFFERING THE TEACHER MEASURES TO MONITOR THE LEARNING PROCESS

Learners can be asked questions that make apparent the holes[413] in common alternative conceptions. For example:

- If current is not used up, but instead goes around in a loop, what does get used up?
- If the battery does not get lighter when it is empty, why do we say that it is empty?
- If the current does not move through the circuit, but is the flow itself, what is it that is moving?

Using the answers form these *formative assessments*, teachers can adjust planning, pacing and give feedback[414], but as Heeg et al. [2020] and

[411] Roschelle [1992]
[412] For example in Mercer [1995], Rojas-Drummond et al. [2006], T'Sas [2018] among many others.
[413] What Muckenfuß [1980] calls "Vorstellungslücken".
[414] C.f. Weatherby et al. [2023]

others have pointed out, doing this is time consuming. Heeg et al. [2020] go about solving this logistical issue by using student drawings to offer a route to speed this process along. Digital tools *afford* the teacher the ability to quickly diagnose these in a way that pen and paper assessment do not allow. Hence, the design requirement to *make assessment easy to enable feedback*.

4.5 *Design of the "Talking Circuits" Application*

A tablet application, "Talking Circuits",[415] was designed and coded in order to integrate these features into a structured and easily implemented workflow in a classroom. The idea was to give teachers a highly-structured and controlled classroom activity in order to allow them to manage how the learners use the iPads and not to increase their workload. This, alongside a booklet following the course, outlined previously in Section 4.1.2, formed the basis for the materials used with experimental group 2 (EG2). The booklet includes sections on static electricity and magnetism too, in order to contain all the content required by the National Curriculum for Electricity and Magnetism more widely and is available here. Other topics did not form part of the intervention and were taught before or after the topics under investigation here.

Figure 4.13: QR Code for the booklet used for experimental group 2.

[415] From here, the app.

4.5.1 *App Overview*

The application was developed in such a way to maximise the number of platforms it could run on, developed using ReactJS. Learners log into the app and have access to an eBook and a simulation. A key *affordance* of an eBook, as designed here, and shown in Figure 4.14, is that information can be displayed in smaller units, ensuring the minimisation of cognitive load via guaranteed *spatial* and *temporal contiguity*, as well as easy segmentation and a high level of specificity when setting reading tasks.

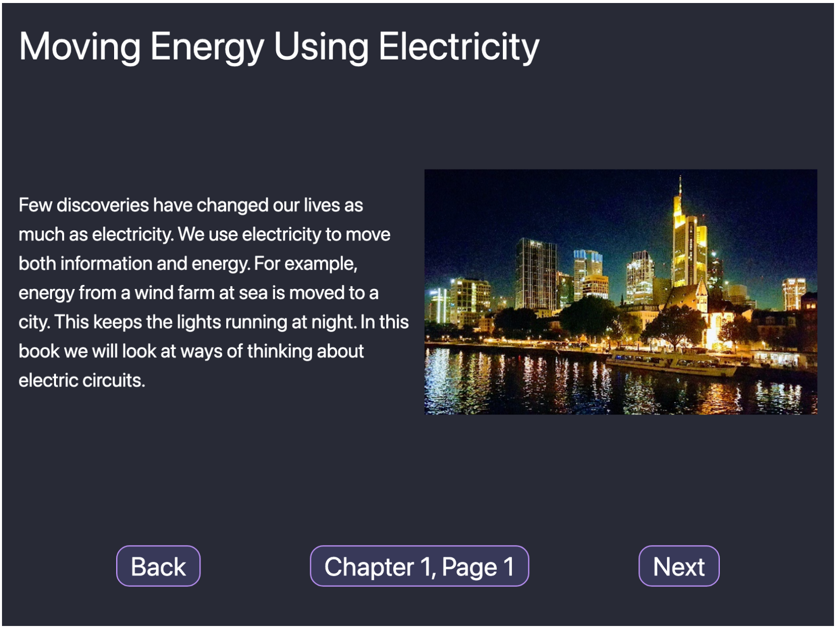


Figure 4.14: Screenshot showing the first page of the eBook version of "An Introduction to Electricity Using Potential Difference".

A simulation is also provided, shown in Figure 4.15, with the visualisations discussed in Section 4.3.3, but as it is not the central object of this intervention. As it has been discussed elsewhere[416], I will omit discussion of it here.

[416] Wilhelm et al. [2021], Weatherby et al. [2020]

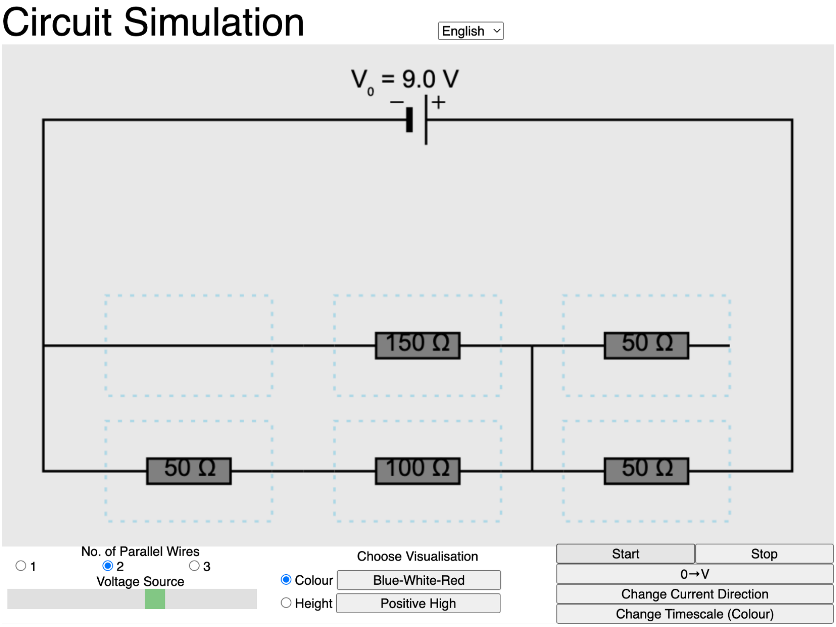


Figure 4.15: Interface of the Circuit Simulation which produce the visualisations shown in Figure 4.5.

The app was also designed to enable the setting and answering of questions for asynchronous homework as well as its use in a *Talk Phase*, which is outlined in the next section, drawing heavily on Weatherby et al. [2022].

4.5.2 *Talk Phase*

The workflow for the *Talk Phase* is the central innovation of this method and builds upon the effective practice outlined in Section 4.4. A typical example of a talk phase in the field of physics education, albeit often at a tertiary level, is during *Peer Instruction*[417]. Despite it being possible in the workflow for *Peer Instruction* to avoid learners working collaboratively at all, the peer talk phase is central in its realisation. As

[417] See Mazur [1997] for an outline and excellent resources for tertiary physics education.

is shown in the left of Figure 4.16, this method includes most of the features listed by Heeg et al. [2020] and discussed in Section 4.4. The method is, however, somewhat complex with branching paths based on answers from the learners. This level of complexity and change in routine can be well implemented with undergraduates, but is less desirable with classes with challenging behaviour at lower secondary. Also, the efficiency gain from moving on when learners answer a question well is not a desirable feature at lower secondary, as the motivation of learners needs to be kept high with learners frequently being successful on tasks. Otherwise, *Peer Instuction* implements the tasks with all the features noted, except features four and six (F4 and F6 from Section 4.4), namely *scaffold involvement for all* and *lead towards consensus*. It could be argued that when used in a university setting, one could expect the learners to be well versed in engaging in academic discussion without needing explicit scaffolding, meaning feature four would be superfluous. Additionally, feature six (*lead towards consensus*), may not be a desirable outcome, depending on the subject and topic. The successes had with this method are indisputable and hence these comments and adjustments are not intended as a repudiation. However, as we are trying to develop a method for lower secondary, these features may be required to support our learners in a way that university students do not require.

Peer Instruction uses "clicker systems"[418] in large lecture settings, either in classroom hardware or software versions such as PINGO or ARSnova. The answers collected are often anonymous and the feedback is given at a whole class level, not allowing for individual feedback, something that becomes possible with smaller groups. Other similar systems may allow for this level of individual feedback such as Socrative or Formative, but are not developed with in classroom, discursive methods in mind. For these reasons a new workflow was developed, shown on the right of Figure 4.16, and integrated into the app, implementing the two missing features, F4 and F6.

[418] Otherwise known as classroom or learning response systems.

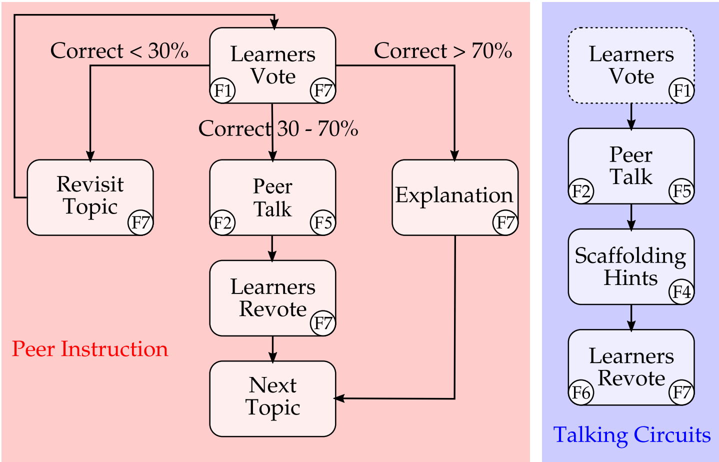


Figure 4.16: Comparing the learning processes between Mazur's Peer-Instruction and the activity structure using *Talking Circuits*. Sub-activities shown in blocks, with features shown inset in circles. Left side of the diagram adapted from Lasry et al. [2008]. Authors work, published in Weatherby et al. [2022].

In the *Talking Circuits* workflow teachers can begin by starting an optional vote individually. However, this is optional, as within the context of a lesson, the ideas present in the questions asked and discussed in peer talk are related to what has come immediately before, so learners are already aware of their own conceptions (F1). This makes it less necessary to have an initial questioning round and of course the sorting function, as in *Peer Instruction*, is not needed. However, Olsen et al. [2019] has shown that the inclusion of this preliminary question is beneficial for learning outcomes. The teacher selects the questions they wish the class to answer, an overview of which is given in Appendix C. To enable a smooth transition into the talk phase, a banner is shown on all learners' devices, as shown at the top of Figures 4.18 and 4.19. This brings learners to a screen with a code and a keypad. On inputting the code of their partner the learners can form groups of two or three. When this is complete the teacher starts the session and learners are shown either the *Question Screen*, shown in Figure 4.18 or the *Talk Screen*, shown in Figure 4.19.

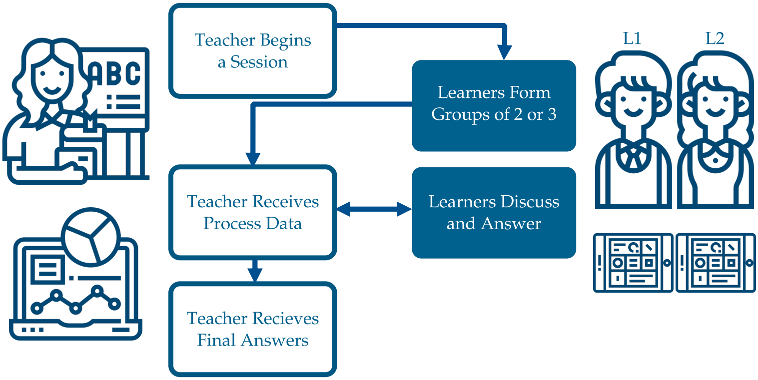


Figure 4.17: Workflow of the Talk Phase in the classroom in terms of concrete actions taken by the teacher and learners. The teacher's actions are shown on the left and learners' actions are shown on the right. Icons are from flaticon.com.

On the *Question Screen* learners can access hints through the "Get a New Hint" button, which reveals up to three hints, beginning to add some scaffolding for feature four. When they have exhausted these, this button changes to "Call the Teacher" and an alert is displayed on the teacher's device. Teachers are also able to see the number of hints requested by the groups who have not called on their help. Both the hints and the "Call the Teacher" button were intended to *afford* learners requesting help in a more anonymous way that makes them less visible to their peers than putting their hands up[419]. It also allows the teacher to keep better track of who needs help and in what order. Learners also select[420] or input[421] their answer on this screen, finally then submitting it. Although, submitting can only be done after completing the tick list on the second screen, necessitating learners working together, fulfilling feature six.

419 Barr [2017]
420 Single or multiple choice.
421 Free-text.

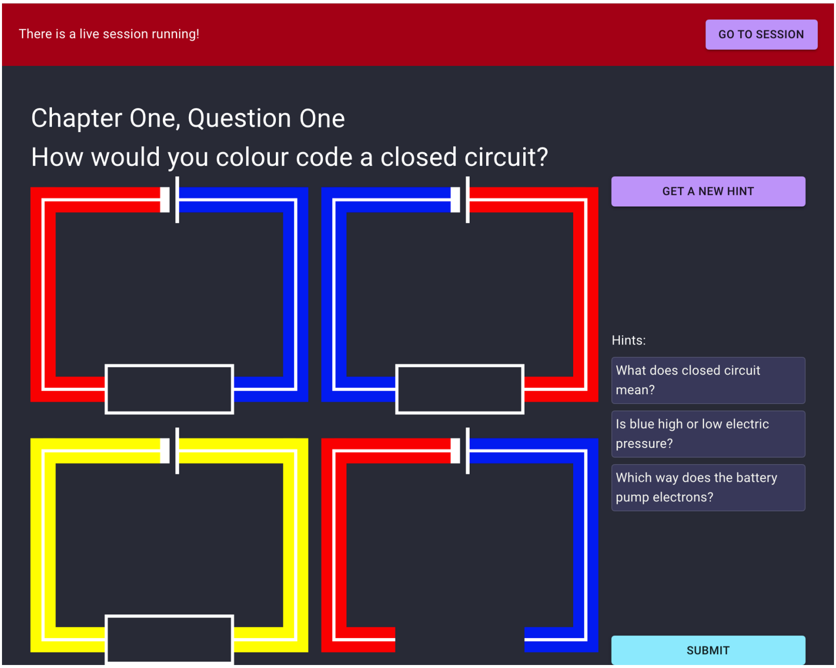


Figure 4.18: Question screen for learner one showing the header that appears for the whole class when a teacher starts a session. Learners can request a hint using the "Get a New Hint" button and receive up to three, as shown here. Learners can also pick an answer option, but can only submit when they have completed the tick-list on learner two's screen, as shown in Figure 4.19.

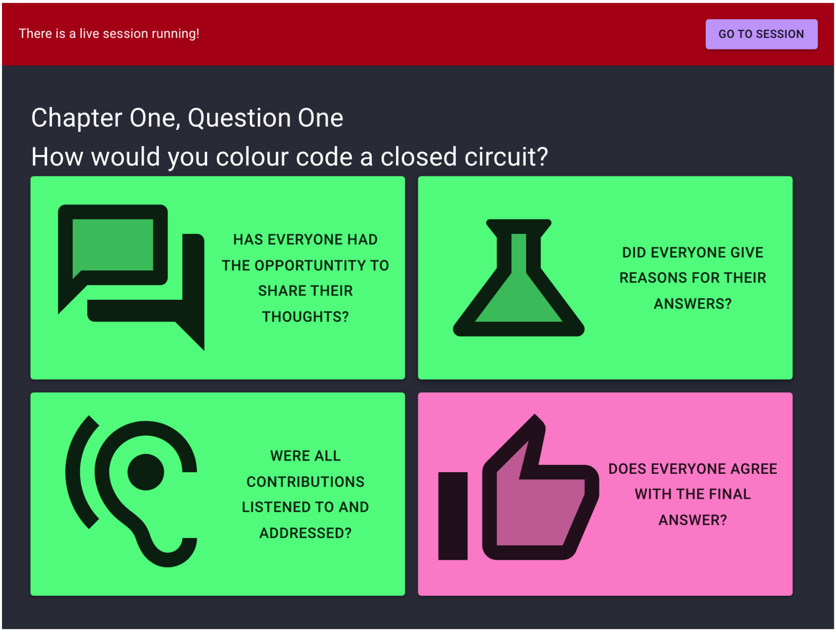


Figure 4.19: Question screen for learner two. Learners must tick the three options in order to submit their answer on learner one's screen, as shown in Figure 4.18.

The *Talk Screen* forms a tick list, rounding out fulfilment of feature four. This tick list is based upon the "Rules for Exploratory Talk"[422]. The three items shown highlighted in green in Figure 4.19 must be ticked before the "Submit" button is shown on the *Question Screen*. "Has everyone had the opportunity to share their thoughts?" and "Did everyone give reasons for their answers?" seeks to address feature two. By ticking "Were all contributions listened to and addressed?" it is hoped that learners take the opportunity to reflect on each others' comments, supporting feature five. However, as I accept that learners may disagree, but the app still requires that they reach a final answer together, the "Does everyone agree with the final answer?" button may remain unhighlighted, hence supporting feature six but not necessitating agreement.

[422] Mercer et al. [1999]

As each group submits, results are shown live to the teacher and then, on finishing the *Talk Phase*, a final report is generated and displayed. On closing the session, a summary of the answers is sent to the teacher via email, so that they can easily keep these to hand to address in other lessons without access to the necessary IT. This allows the teacher measures to monitor the learning process, feature seven.

It may be noted that neither process, *Peer Instruction* or the *Talk Phase*, addresses feature three. This is because this feature is achieved on the level of question writing and the context that is asked. All the contexts are built upon material that is in the preceding lesson, so there should be a common *situation model* present.

This talk phase was carried out in a total of five lessons in the ten lesson pack for EG2. All the questions were completed by all the learners and anonymised logging data was collected. The questions that were asked are shown in Appendix C and the lesson numbers shown there correspond to the lesson numbers from the booklet.

4.6 Research Questions and Study Design

Using all these outlined materials a study was carried out to investigate their efficacy, specifically with regards to learning gains and motivation. This was done as part of standard science lessons in year eight across one multi-academy trust in the south-east of England.

4.6.1 Research Questions and Hypotheses

The resources outlined in the previous section are used to examine the following research questions:

RQ1: Are learning gains increased through the use of this Computer Supported Collaborative Method?

RQ2: Are aspects of student motivation regarding learners' "physics lessons" increased through the use of this Computer Supported Collaborative Method?

RQ3: Are aspects of student motivation regarding "talking about science" increased through the use of this Computer Supported Collaborative Method?

Regarding RQ1, inline with research discussed in Section 4.4, I expect the EG2 to show increased learning gains over EG1. Hence I formulate Hypothesis H1:
H1: Learning gains for EG2 will be higher than for EG1.

As there are three sub-scales measured, with regards to RQ2, as outlined in Section 2.1.5, a hypothesis is generated for each. As learners show a desire for more discussion or collaboration in their science lessons[423] and many examples of computerised methods increasing motivation[424], I expect all sub-scales to improve. Some caveats to this are discussed in Section 2.1.5 and later in the discussion.
H2a: Interest and Enjoyment gains for EG2 will be higher than for EG1.
H2b: Perceived Competence gains for EG2 will be higher than for EG1.
H2c: Felt Pressure gains for EG2 will be lower than for EG1.

There is little data to make hypotheses regarding RQ3, hence these will be examined exploratively. Interactions of concept knowledge and motivation with gender and each other are also examined exploratively.

[423] Juuti et al. [2010], Teppo et al. [2021]
[424] C.f. Treagust and Tsui [2014].

4.6.2 *Study Design and Time Plan*

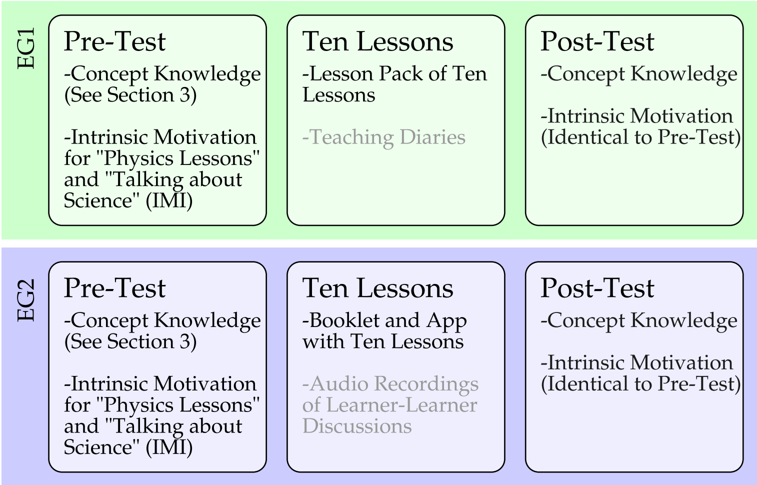


Figure 4.20: Timeline for Experimental Groups 1 and 2. Green background shows the timeline in Winter 2021-22 and the blue background shows the timeline in Winter 2022-23. Grey text shows parts not discussed in this thesis.

In order to test the aforementioned hypotheses, the following study design, as indicated in Figure 4.20, was carried out over the winter terms of 2021-22 and 2022-23. Learners filled out the same test as pre- and post-test, consisting of the Concept Knowledge test redeveloped and discussed in Chapter 3 and given in full in Appendix A.2. In addition to this, three scales of the IMI are contained, as shown in Table 4.6. Both experimental groups completed a set of 10 lessons with the same content and structure. Teaching diaries were distributed as part of the material pack for EG1, with the hope of insuring implementation fidelity, but none were returned and hence cannot be discussed. During the intervention for EG2, audio recordings as well as answer logs were kept for the *Talk Phases* whilst learners were answering questions. These are beyond the scope of this thesis, however, and are intended for presentation at a later date.

Sub-Scale	IMI No	Inv.	Text
P	2	✓	I do not feel at all nervous [].
C	4		I think I am pretty good at [].
I	5		I find [] very interesting.
P	6		I feel tense while in my [].
I	8		[] are fun.
P	9	✓	I feel relaxed while [].
C	12		I am satisfied with my performance [].
I	14	✓	I think [] are very boring.
C	16		I feel pretty skilled at [].
P	18		I feel under pressure while [].
I	20		I would describe [] as very enjoyable.
C	PC6	✓	[], is something I can't do very well.

Table 4.6: Table showing Intrinsic Motivational Inventory (IMI) Items used in the intervention. [] indicates words that indicate the context. Two contexts are asked during the study: "physics lessons" and "talking about science". The column "Sub-scale' indicates which *Self Determination Theory* subscale is measured by the item: "Felt Pressure" (P), "Perceived Competence" (C) and "Interest and Enjoyment" (I). "IMI No" refers to the number of the item in the "Task Evaluation Questionnaire", plus one item from the full Inventory, the sixth question in the "Perceived Competence" scale. The entire IMI is available here. "Inv." shows if a scale is inverted.

5 *Results of the Quasi-Experimental Study*

Like most things, good teaching is ultimately an art that is informed by science

– Paul A. Kirschner and Carl Hendrick,
How Learning Happens

Chapter Contents

5.1 *Data Collection and Preparation*

	Pre	Post	Match	%
EG1	146 (6)	146 (6)	116 (6)	79.5%
EG2	154 (6)	123 (6)	112 (5)	80.9%

Table 5.1: Summary of Learner and Class Numbers (in brackets), matching percentages. 4 teachers taught across the 6 classes in each experimental group, only one teacher took groups in both experimental groups. No matches can be found for one class in EG2.

This chapter will examine the concept knowledge and affective outcomes of the two different interventions presented in this dissertation. Concept knowledge outcomes refer to the differences in progress made on the subject of electricity. Affective outcomes refer to changes in learners' intrinsic motivation with regards to both "physics lessons" in general and "talking about science". These variables are examined through pre- and post-testing either side of the two interventions. The first of which, experimental group 1 (EG1), was conducted with teachers using traditional (pen and paper) resources[425] that use the analogy of *electric pressure* with no direction on method of delivery. Experimental group 2 (EG2) used materials with the same content and structure, but used the "Talking Circuits App" in addition, in order to scaffold learner-learner dialogues.

In order to take data, teaching resources were distributed to 5 schools. One school withdrew before conducting EG1 and three schools only completed EG1 and not EG2. This left only one school completing the whole quasi-experimental trial. Totals for number of learners participating, with those able to be matched in both pre- and post-data, are shown in Table 5.1. Only matching data for this school is used in the following analysis. This withdrawal was due to a variety of factors, some school and staffing specific, but also due to the ongoing effects of the COVID-19 pandemic.

[425] The concepts behind and redevelopment of which are outlined in Section 4.3.

5.1.1 Data Collection

Due to the effects of the COVID-19 pandemic, data was gathered on paper for EG1 pre-test and for all other tests digitally. There is no significant difference in pre-test results gathered on paper or digitally, t-test $p = 0.0546$. This is in line with other concept test results gathered in this way[426]. Despite being not significant, the change in concept score averages on the pre-test change from 2.78 to 3.30, between EG1 and EG2, may confound the effect of the intervention, as average changes across the intervention are only around 1-2 marks.

5.2 Effect of the Intervention on Attainment

In order to examine RQ1 the attainment scores on the knowledge test are analysed using both a repeated measures ANOVA of the scores on the concept test[427] and a pre to post score difference using the Mann-Whitney-Wilcoxon-Test.

Each sub-question is marked with a binary value, indicating as to whether the question was answered correctly or not. Only if all the sub-questions are answered correctly, is then an entire question marked as correct, again assigned in binary. A plot showing the distributions of the scores can be seen in Figure 5.1, as well as numerically in Table 5.2. Given that the maximum score of the test is 27, there can be no plausible ceiling effects. It may appear plausible that there would be floor effects as there are scores recorded as 0. However, there is no shoulder visible and the lowest score does not constitute 15-20% of the data set[428], even in the pre-tests (9 of 116 and 8 of 112, circa 8 and 9% respectively).

Another cause for concern may be the unmet conditions given in text books for using Repeated Measures (RM-)ANOVA e.g. Kassambara [2019]. These unmet conditions are: a) extreme outliers as seen in Figure

[426] Seiter [2022, p. 171]
[427] Detailed in Chapter 3.
[428] McHorney and Tarlov [1995] in Garin [2014]

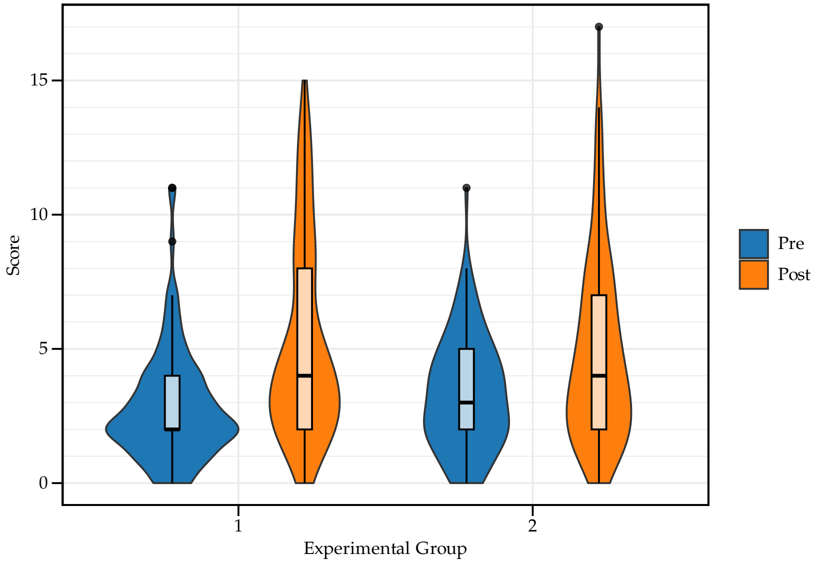


Figure 5.1: Violin with Overlaid Box-and-Whisker Plots Showing Pre- and Post-Test Scores for Both Experimental Groups.

	Pre		Pos	
	Mean	SD	Mean	SD
EG1 ($N = 116$)	2.78	2.04	5.16	3.60
EG2 ($N = 112$)	3.30	2.08	4.84	3.36

Table 5.2: Pre- and Post-Test Score Means with Standard Deviations for Both Experimental Groups

5.1, although not many, totalling only 4 of 456 observations. b) highly non-normal nature of the distribution, as $N > 50$ in this case this is examined using a QQplot shown in Figure 5.2. This plot shows extreme residuals outside allowed areas shown in grey. However, Blanca et al. [2023] show RM-ANOVA not to be sensitive to extreme non-normality across a range of sample sizes ($10 \geq n \geq 300$), so the analysis can be carried out regardless.

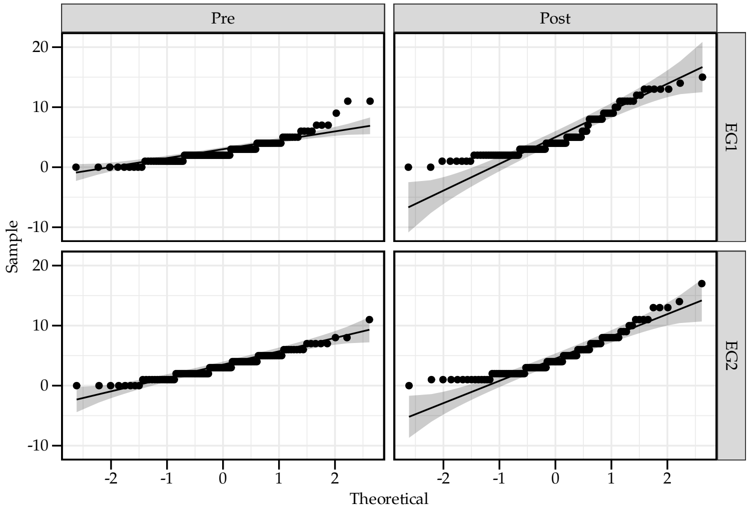


Figure 5.2: Pre- and Post-Test Residuals for Both Experimental Groups

Table 5.3 shows the results of this analysis. The first row shows that there is no significant difference in score between the experimental groups, with $p = 0.74$. The second row shows the significant difference between pre- and post-tests, i.e. a significant learning gain with a medium effect strength, $0.06 \leq \eta^2 < 0.14$[429]. The third row of the table shows the interaction between experimental group and time, it is marginally not significant with $p = 0.059$. This would be the value that evidenced whether the intervention had had an effect. This leaves us unable to reject the null hypothesis to RQ1, as no significant learning gain differences, shown by an interaction, are measurable.

[429] Cohen [1988]

Effect	DFn	DFd	F	p	$p < .05$	η^2_G
Experimental Group (EG)	1	226	0.110	.74		3.18e-4
Time (Pre or Post)	1	226	76.565	5.0×10^{-16}	✓	0.1076
EG:Time	1	226	3.612	.059		6.00e-3

Table 5.3: ANOVA Summary for Pre- and Post-Test Scores. DFn are the degrees of freedom in the numerator, DFd are the degrees of freedom in the denominator, F is the F-test statistic (a measure of divergence from an expected variance), p is the p-value, and η^2_G is the generalized Eta-Squared measure of effect size.

	Mean	SD
EG1 ($N = 116$)	2.39	3.45
EG2 ($N = 112$)	1.54	3.32

Table 5.4: Means with Standard Deviations of Score Difference for Both Experimental Groups.

Huck and McLean [1975] suggest that comparing differences (learning gains) in score in pre- and post-test, shown in Table 5.4, in a simple comparison is to be preferred for ease of interpretability. As the difference in score is also highly non-normal, visible in Figure 5.3, the Mann-Whitney-Wilcoxon-Test is used. This similarly leaves us unable to reject the null hypothesis to RQ1, with $p = 0.0798$.

As discussed in Section 3.3, the test seems to have been significantly too difficult for the learners in this cohort. This limits the resolution achievable and the power of the conclusion that can be drawn from the data. Learning gains for experimental group 1 (EG1) are somewhat higher but not significantly higher than experimental group 2 (EG2). This may be attributed to the increase in pre-test scores in EG2, likely due to the necessity to collect them digitally and digital collection only adding data to the database on the completion of the full questionnaire. Hence, leading to higher average completion rates and therefore higher scores. In conclusion, and even with these caveats are taken into account, there is no significant difference in learning gains across the whole cohort measured between the two intervention groups.

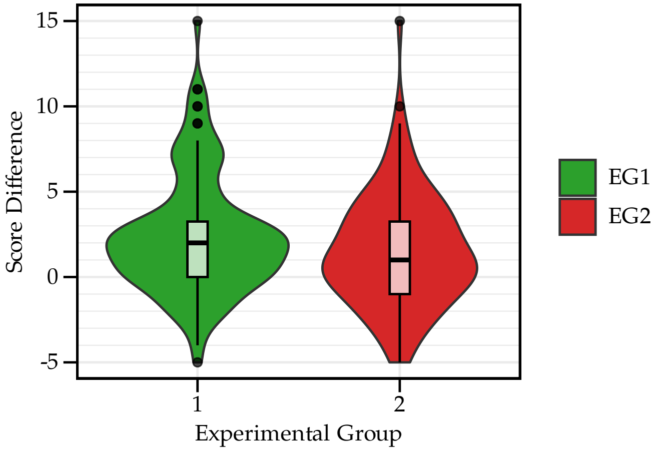


Figure 5.3: Violin with Overlaid Box-and-Whisker Plots Showing Score Differences for Both Experimental Groups.

5.3 *Effect of the Intervention on Motivation*

IMI Sub-Scales	Int.	Pres.	Comp.
Physics Lessons	0.88	0.67	0.82
Talk about Science	0.89	0.67	0.87

Table 5.5: Cronbach's Alpha for Each IMI-Subscale.

Aspects of intrinsic motivation were tracked using three sub-scales of the Intrinsic Motivation Inventory (IMI): Interest and Enjoyment (Int.), Felt Pressure (Pres.) and Perceived Competence (Comp.), shown as an overview in Figure 5.4 and numerically in Table 5.6. These three sub-scales are asked in two contexts "my physics lessons" and "talk about science". The text given in quotation marks is inserted into the square brackets in the questions shown in Table 4.6. Higher scores on the interest and competence subscales indicate higher motivation, whereas higher scores on the pressure subscale represent lower motivation. As can be seen in Table 5.5, α_{Cronbach} for the interest and competence subscales are above the 0.7 generally deemed acceptable in Science Education Research[430], but the pressure sub-scale falls below this. This is likely due to the strong floor effects seen within the two items "I feel tense while..." and "I feel under pressure while...", with 27 and 28% answering the lowest option on a 7 point Likert-Scale. This must be borne in mind when judging the interpretability of this scale.

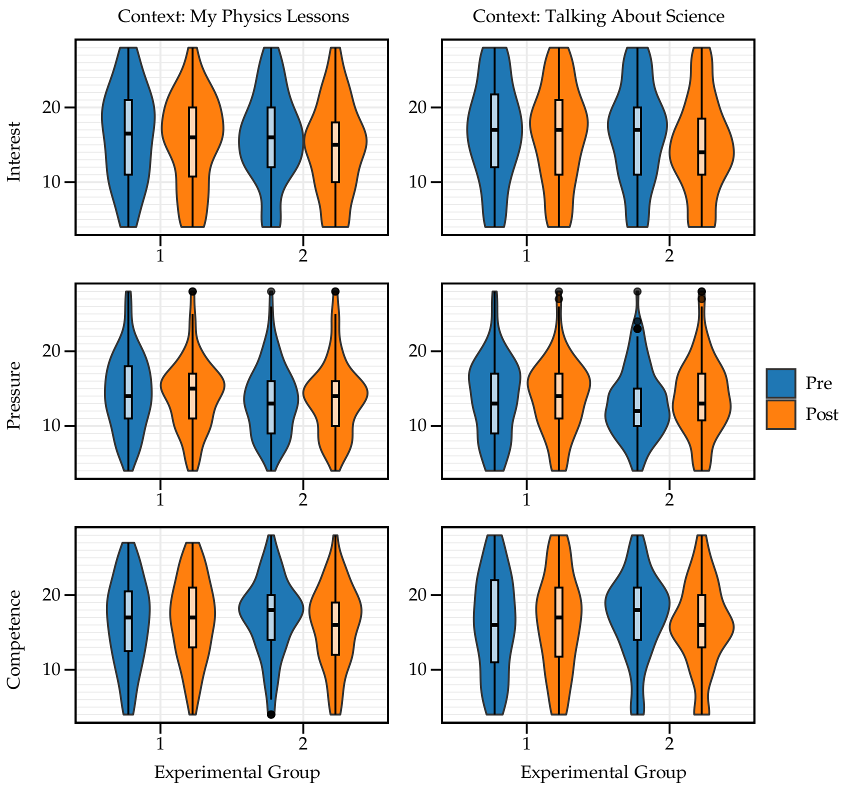


Figure 5.4: Violin with Overlaid Box-and-Whisker Plots Showing Intrinsic Motivation Inventory Sub-Scales for Both Experimental Groups.

As can be seen in Table 5.7, all effects are of negligible effect strength,

[430] Taber [2018b]

		My Physics Lessons								
		Interest			Pressure			Competence		
		N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
EG1	Pre	102	16.25	6.46	106	14.43	5.21	107	16.28	5.83
	Pos	116	15.44	6.22	116	14.05	4.73	116	16.72	5.62
EG2	Pre	111	15.95	6.09	111	13.31	4.72	111	17.04	5.14
	Pos	111	14.52	6.25	111	13.55	4.87	111	15.96	5.42
		Talking About Science								
		Interest			Pressure			Competence		
		N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
EG1	Pre	98	16.67	6.82	102	13.64	5.47	101	16.07	6.69
	Pos	116	16.11	6.68	116	13.84	4.93	116	16.38	6.60
EG2	Pre	111	16.25	6.70	111	13.10	4.72	111	17.17	5.69
	Pos	111	14.84	6.52	111	13.73	5.19	111	15.95	5.86

Table 5.6: Means and Standard Deviations for Each Measurement Point of the IMI Subscales. Changes in *N* are due to incomplete datasets.

$\eta^2 < 0.01$[431]. There are, however, significant effects of change (reduction) of interest and enjoyment in both "physics lessons" and "talking about science". This stands in contrast to Burde et al. [2020], using the interest scale developed by Dopatka et al. [2020] who measure a significant, albeit low, increase in interest when teaching the subject of electricity in 'Gymnasien' (Grammar schools) in Germany and Austria under "status quo" conditions. However, the German materials my study is based upon[432] were not viewed by teachers as particularly building interest and motivation in learners[433]. There is a significant interaction effect measured for Interest and Enjoyment regarding "talking about science". This effect is below the $\alpha < 0.05$ threshold, but not clearing a lower, Bonferroni corrected threshold. The Bonferroni correction is applied "family wise", but it is difficult to judge as to which of the variables falls into a family. As the effect-strengths are very

431 Cohen [1988]
432 i.e. not "status-quo" conditions.
433 Burde [2018, p. 276]

low in all cases, it changes our interpretation of results and practical outcomes very little, in either case. This statistically, but not practically, significant difference in response could be due to the fact learners had only associated "talking about science" with an activity outside of school (they did very little discussion work before this) and as it became part of science lessons and compulsory[434], this acts to reduce interest. The evidence does not support H2a.

There is no evidence that learners feel a change in pressure in their physics lessons or when talking about science. The data do not support hypothesis H2c.

There are statistically (but not practically) significant reductions in "Perceived Self Competence" with regards to both "physics lessons" and "talking about science". This could be interpreted as learners being confronted by their own misconceptions, when having to actively engage in discussion. This finding is inline with similar results from cognitive conflict approaches, i.e. Dreyfus et al. [1990] note that weaker prior attaining learners develop negative attitudes towards school. The evidence does not support H2b, to the contrary, the evidence suggests a reduction in physics related perceived self competence through the intervention.

Results for pre-post differences, shown visually in Figure 5.5 and numerically in Table 5.9, tested for differences using the Mann-Whitney-Wilcoxon-Test with key parameters, shown in Table 5.8. These data and statistical tests produce results inline with the RM-ANOVA tests shown in Table 5.7, hence my interpretation remains the same as that to those results discussed in the previous paragraph. The Mann-Whitney-Wilcoxon-Test is used in all cases, as the data is quite strongly non-normal, which can be seen from the violin plots in Figure 5.5 and in the fact that multiple sets of data fail the Kolmogorov-Smirnov-Test for

[434] i.e. a removal of autonomy. Perceived autonomy, another IMI subscale, was not measured in this test.

Interest and Enjoyment: Physics Lessons					
Effect	DFn	DFd	p	$p < \alpha$	η^2_G
EG	1	211	0.422		3e-03
Time	1	211	0.001	✓	8e-03
EG:Time	1	211	0.322		7e-04

Interest and Enjoyment: Talking About Science					
Effect	DFn	DFd	p	$p < \alpha$	η^2_G
EG	1	207	0.256		6e-03
Time	1	207	0.004	✓	4e-03
EG:Time	1	207	0.041	(✓)	2e-03

Felt Pressure: Physics Lessons					
Effect	DFn	DFd	p	$p < \alpha$	η^2_G
EG	1	215	0.155		8e-03
Time	1	215	0.929		6e-06
EG:Time	1	215	0.331		8e-04

Felt Pressure: Talking About Science					
Effect	DFn	DFd	p	$p < \alpha$	η^2_G
EG	1	211	0.593		1e-03
Time	1	211	0.165		2e-03
EG:Time	1	211	0.495		4e-04

Perceived Self Competence: Physics Lessons					
Effect	DFn	DFd	p	$p < \alpha$	η^2_G
EG	1	216	0.946		2e-05
Time	1	216	0.33		7e-04
EG:Time	1	216	0.006	✓	5e-03

Perceived Self Competence: Talking About Science					
Effect	DFn	DFd	p	$p < \alpha$	η^2_G
EG	1	210	0.666		8e-04
Time	1	210	0.123		1e-03
EG:Time	1	210	0.013	(✓)	4e-03

Table 5.7: ANOVA Summary for Pre- and Post-Test Scores. DFn are the degrees of freedom in the numerator, DFd are the degrees of freedom in the denominator, F is the F-test statistic (a measure of divergence from an expected variance), p is the p-value, and η^2_G is the generalized Eta-Squared measure of effect size. A tick in brackets indicates $p < .05$ and a tick without brackets indicates significance holds below the Bonferroni corrected threshold also.

IMI Sub-Scales		p	$r = \frac{Z}{\sqrt{n}}$
Phys.	Int.	0.636	0.0325
	Pres.	0.522	0.0435
	Comp.	0.00781	0.180
Talk	Int.	0.00860	0.182
	Pres.	0.272	0.0753
	Comp.	0.0471	0.136

Table 5.8: p-Statistics and Effect Strengths for pre-post differences in each IMI sub-scale.

normal distributions. Therefore, for ease of interpretation, I interpret all data using the same metrics.

My Physics Lessons									
	Interest			Pressure			Competence		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
EG1	102	-.76	5.36	106	-.29	4.36	107	.53	4.42
EG2	111	-1.42	4.31	111	.24	3.73	111	-1.07	4.19
Talking About Science									
	Interest			Pressure			Competence		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
EG1	98	-.24	4.22	102	.22	4.28	101	.29	4.93
EG2	111	-1.41	4.00	111	.63	4.56	111	-1.23	3.86

Table 5.9: Means and Standard Deviations for Each Difference of the IMI Subscales. Changes in N are due to incomplete datasets.

There are significant differences, below Bonferroni threshold, for two scales at small effect sizes $r < 0.3$[435]. These imply that the learners in EG2 have significantly lower perceived self competence in their physics lessons and show significantly less interest and enjoyment about talking about science after talk has been introduced as a learning tool in their

435 Cohen [1988]

physics lessons. In short, active talk is likely to make learners aware of their misconceptions and induce cognitive conflict, which, as the cohort is not high prior attaining, seems to have had an adverse impact on their perceived self competence. Pupil interest and enjoyment when "Talking about Science" may also have been adversely impacted in the second experimental group, as discussion was not a normal part of the learners' science lessons before, so they did not associate it with school. This link to school with explicit talk centred instruction seems to have reduced their interest and enjoyment with regards to it, either through the removal of autonomy, by making it a mandatory part of science lessons, or some other mechanism.

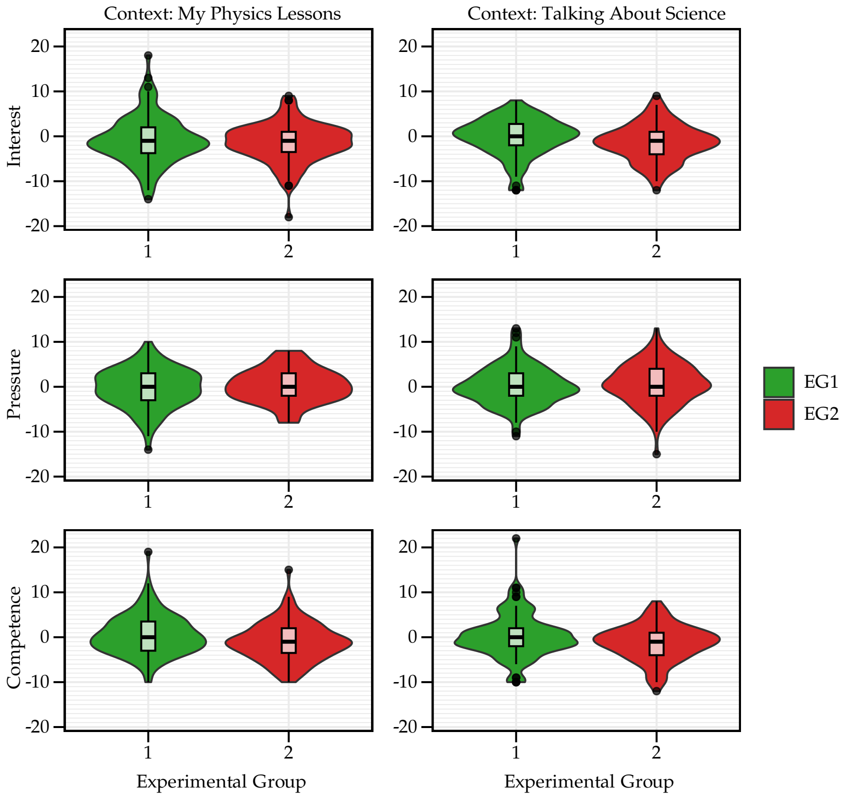


Figure 5.5: Violin with Overlaid Box-and-Whisker Plots Showing Intrinsic Motivation Inventory Sub-Scale Differences from pre- to post-test for Both Experimental Groups in two contexts "my physics lessons" and "talking about science". "Interest", "Pressure" and "Competence" are the subscales of the intrinsic motivation inventory "interest and enjoyment", "felt pressure" and "perceived competence".

5.4 *Effects for the Same Teacher*

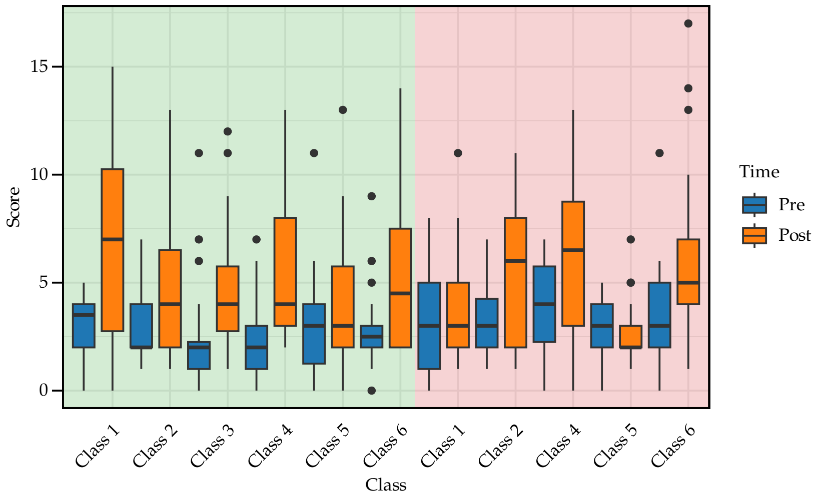


Figure 5.6: Box-and-Whisker Plots Showing Concept Test Scores from pre- to post-test for Both Experimental Groups, separated into classes. Green and red backgrounds denote EG1 and EG2, respectively.

Due to the effect the teacher has on learning outcomes, it is desirable to keep teachers the same across both intervention groups. One can even design experiments that have a cross design that takes out the variable of teachers becoming more practised, e.g. Lutz and Trefzger [2019]. The variation of the learning gains by class can be seen in Figure 5.6. Class 3 is missing in EG2 as there were only 5 learners in the post-test and none could be matched to the pre-test. Due partially to high turn-over of staff at the school, there was only one teacher present in both experimental groups, teaching class 2 in EG1 and classes 2 and 4 in EG2. Data for his classes is shown in Table 5.10. This teacher was in his first year of teaching, post training, during EG1.

	EG1			EG2					
	Class 2			Class 2			Class 4		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
Pre	25	2.96	1.88	21	3.05	1.91	22	3.91	2.24
Post	25	5.32	3.56	21	5.43	3.09	22	6.41	3.65

Table 5.10: Mean and Standard Deviations for Concept Scores in Classes Taught by a Single Teacher.

Effect	DFn	DFd	F	p	$p < .05$	η^2_G
Experimental Group (EG)	1	63	1.857	0.178		0.0192
Time (Pre or Post)	1	63	24.961	4.93×10^{-6}	✓	0.1233
EG:Time	1	63	0.189	0.665		0.001

Table 5.11: ANOVA Summary for Pre- and Post-Test Scores, for a single teacher. DFn are the degrees of freedom in the numerator, DFd are the degrees of freedom in the denominator, F is the F-test statistic (a measure of divergence from an expected variance), p is the p-value, and η^2_G is the generalized Eta-Squared measure of effect size.

Selecting the data from only his classes yields similar interpretations as for the whole data set, both when using a RM-ANOVA, as shown in Table 5.11 and in comparing gains from pre- to post-test, yielding $p = 0.416$ in a Mann-Witney-Wilcoxon-Test. Even if there had been a measurable effect here, whether this would have been due to a development effect of the teacher or due to the intervention, would have been difficult to disentangle, as the teacher was teaching electricity for the first time in EG1.

In conclusion, using only data from the one teacher present in both experimental groups, shows no significant difference in intervention groups.

5.5 *Effects by Alternative Conception*

		CU	BCC	CIIR	IR	HRHC	LA	SA	POC	GPC	RGC	CIR	CP
Case Count		4	4	4	3	3	3	4	3	3	3	3	3
EG1 ($N = 116$)	Pre	94	37	46	55	22	70	53	58	43	65	7	31
	Pos	92	54	54	39	41	109	68	76	31	47	24	35
EG2 ($N = 112$)	Pre	119	53	29	54	33	83	40	95	45	95	19	60
	Pos	100	39	57	38	54	97	51	63	28	37	15	34
Occurrence Rate		CU	BCC	CIIR	IR	HRHC	LA	SA	POC	GPC	RGC	CIR	CP
EG1 ($N = 116$)	Pre	0.203	0.080	0.099	0.158	0.063	0.201	0.114	0.167	0.124	0.187	0.020	0.089
	Pos	0.198	0.116	0.116	0.106	0.118	0.313	0.147	0.218	0.089	0.135	0.069	0.101
EG2 ($N = 112$)	Pre	0.266	0.118	0.065	0.161	0.098	0.247	0.089	0.283	0.134	0.283	0.057	0.179
	Pos	0.223	0.087	0.127	0.113	0.161	0.289	0.114	0.188	0.083	0.110	0.045	0.101

Table 5.12: Tables showing: Above) The number of occurrences of each coded alternative conception. Maximum possible number of occurrences is N times the number of cases. Below) The rates of each occurrence as a proportion of the maximum possible occurrences. Codes are sequential from the *alternative conceptions* in the Table in Appendix A.3.

Unlike the concept test scores that were judged to not be significantly different, using a test of two proportions (Z-test) on the rates of cases across all *alternative conceptions*, occurrence rates of *alternative conceptions*, shown in Table 5.12, are judged significantly different for tests filled out digitally and on paper, $p = 6.02 \times 10^{-7}$, by comparing pre-tests from EG1 (on paper) and EG2 (digital). This may stem from 16.7% of the diagnosis cases containing missing data, consequently marked `NaN`, and therefore could not be counted. However, there was a 28.8% increase of *Alternative Conceptions* cases when measured digitally, which suggests another mechanism is at work. The differences of the pre-test rate can be seen on the upper axes of Figure 5.7. The y-axis shows the occurrence per coding case, i.e. for CU (Current Use) there are 4 cases[436], a maximum of 1 is possible if all 4 cases are true for all learners and 0 in the case that no learners give a single one of the four answer combinations. In experimental group 1 (EG1) the pre-test group is measured on paper, where as all other test points are measured

[436] Corresponding to 4 answer combinations shown in Appendix A.3

digitally. As the test method seems to change diagnosis probability, leaving us unable to control for pre-test rates, only the post-test rates are compared, which are both measured digitally.

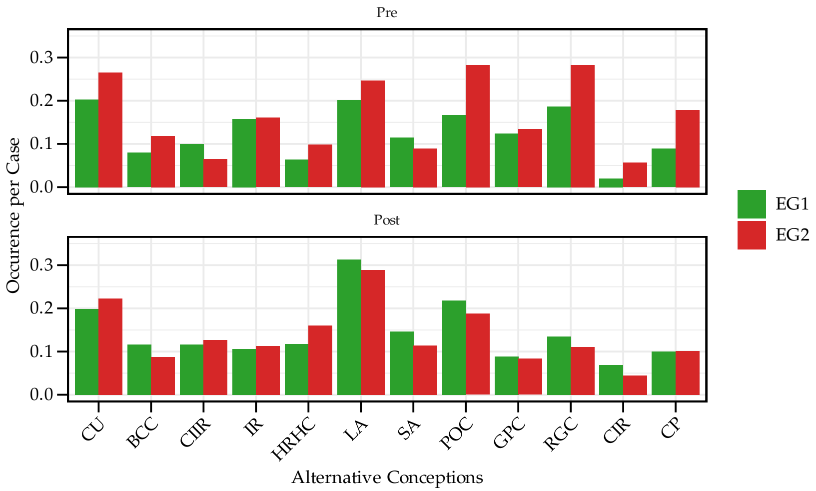


Figure 5.7: Bar charts showing the Pre- and Post-Test Rates of Alternative Conceptions. Codes are sequential from the *alternative conceptions* in the Table in Appendix A.3.

These rates of occurrence are compared using the two proportions z-test again, the p-values for which are given in Table 5.13. No *alternative conception* is diagnosed at a significantly different rate after each intervention. Acronyms correspond to *alternative conceptions* in the Table in Appendix A.3. Assuming rates of *alternative conceptions* in the pre-test are constant across the groups, this implies that the method of intervention does not significantly change the rates of *alternative conceptions* shown after the intervention.

	Total	CU	BCC	CIIR	IR	HRHC	LA	SA	POC	GPC	RGC	CIR	CP
p	0.327	0.356	0.144	0.616	0.924	0.105	0.485	0.143	0.316	0.789	0.321	0.170	0.979

Table 5.13: Table showing the p-values for a two-proportions Z-Test, none of which are judged to be significantly different. Codes are sequential from the *alternative conceptions* in the Table in Appendix A.3.

5.6 Conclusions and Suggestions for Future Research

5.6.1 Concept Knowledge Outcomes

This research was able to show that the use of a computer supported collaborative learning tablet application for scaffolding peer talk was unable to increase the concept related learning outcomes (differences of pre- and post-scores scores in a t-test: $N = 228$, $p = 0.0798$). The conditions to measure this were not ideal. Due to effects of the COVID-19 pandemic and staffing issues in partner schools, all but one school withdrew from the project. Also due to COVID-19 related issues questionnaires had to be taken in a mixture of electronically and on paper, impacting comparability. There was also only one teacher who took part in the two interventions who, despite achieving improving outcomes from EG1 to EG2, did not see *significant* improvement between the two experimental groups ($N = 64$, $p = 0.416$).

According to Howe and Abedin [2013], there were no interventions of the nature of the study conducted here, i.e. target-based quantitative investigations, published before 2013. However, Mercer et al. [2004][437] seems to meet these criteria. Of interest, learners used an interactive simulation to predict basic scientific outcomes (i.e. what material would be a better insulator of sound) and were prompted by the programme to "Talk together to decide and say your reasons why"[438]. Learners were given explicit instruction on peer talk, teaching staff were trained and the intervention took place over 23 weeks. Learners in the intervention group ($N = 119$) increased their scores on standardised attainment

[437] Also reported in Dawes [2004].
[438] Wegerif [2004, p. 184]

tests pre- to post more than those in the control group ($N = 129$), with a moderate effect size[439]. Another example of where an intervention like this has been published since 2013 and shown to be successful is Hanley et al. [2015]. During this study, teaching staff received training, learners were instructed in how to engage in talk and the intervention was conducted long term. In more detail, Hanley et al. [2015] conducted a year long intervention with year 5 (primary), which provided teachers with a well-attended set of five, day-long training sessions.

It would seem that scaffolding through a tablet application is unable to substitute for these seeming success criteria of: a) a longer intervention, b) explicit talk lessons and c) teacher training. In contrast, the intervention here was carried out in a short time, a 12 lesson block. The "content rich" secondary science curriculum did not afford time for "talk lessons" and the constraints of COVID-19 and being a one man team did not allow time for teacher training. There is also a question as to the embedding of such an approach into Key Stage 3 and whether more open "predict-observe-explain" tasks would be more appropriate for the use of peer talk.

Due to time constraints, I have been unable to review the audio recorded from the learners whilst using the application. These learner-learner conversations would provide indicators as to whether the talk is productive. If it could be shown that the talk is widely productive, it would show that the digital scaffold achieves some of the success criteria that Mercer [1995] argues comes from explicit instruction on productive talk.

Future work could integrate a tablet application into an already successful intervention and examine whether it improves the implementation of peer dyadic talk. A longitudinal comparative study could also be carried out examining the way in which scaffolding of this type impacts the time taken for learners to transition to productive talk throughout an intervention. This could be examined both in the sense of limiting

[439] Mercer et al. [2004, p. 371]

"transition time" between activities[440] and in the sense that learners may internalise the features of productive talk faster through prompting and scaffolding. Activities could also be substituted within the same topic, with concept questioning compared with "predict-observe-explain" style tasks.

A necessary step for further research in this field would be the development of a psychometrically robust, school curriculum relevant, lesson length concept test to measure concept knowledge and *alternative conceptions* on the topic of electricity, as argued repeatedly throughout this thesis[441].

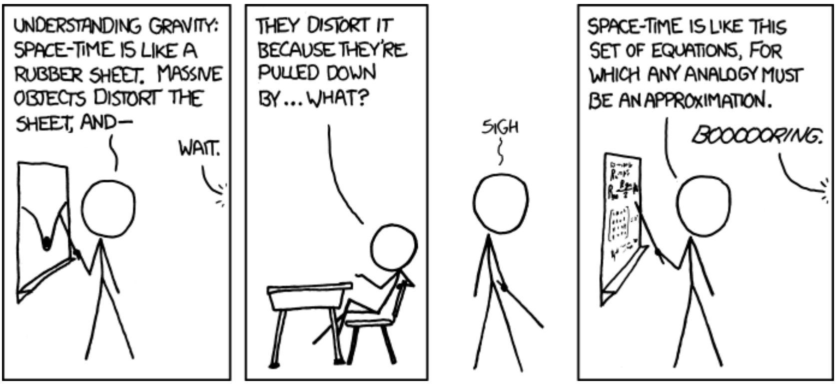
5.6.2 Motivational Outcomes

There were, however, significant changes in sub-scales of the intrinsic motivation inventory. Learners had significantly less perceived self competence after using the tablet application in their lessons. This stands in contrast to previous findings. Firstly, in Hanley et al. [2015], where increases in positive attitudes are reported, although not explicitly those measured in my study. Secondly, in Hawksworth [2023] in which an intervention was run for around 4 months for thirty year 9 learners in tutor time, explicitly on oracy. Their increase in confidence was both self reported (although low statistic) and evidenced through pre- and post-recordings that show "the change of tone in their voices to sound more confident, post intervention"[442]. A possible reason for this discrepancy could be the explicit instruction about speaking in the classroom and that it is a tool where the goal is for learners to justify their thinking, rather than being right or wrong. In short, that the success criteria are different to what might happen in a usual science lesson.

[440] Hence, increasing "time-on-task" and therefore learning outcomes, as shown in meta-analyses, Hattie [2009], Scheerens et al. [2013].
[441] See Section 3.3 for a longer discussion.
[442] Hawksworth [2023, p. 48]

Further research could be done on the levels of perceived self competence (or other affective measures) over the course of a longer intervention, looking at how learners' affect changes throughout, through repeat measurements across sessions. Also of note, is the role of cognitive conflict and how this plays a central role in science education, but less in other subjects. Hawksworth [2023], for example, had learners discuss open-ended, ethical questions without real "correct answers". This may also have a mediating influence on learners' perceived self competence and enjoyment, as the answers are necessarily more directed in scientific topics and a learner can answer unscientifically and therefore perceive themselves as being "wrong". This could be investigated by using the same instructional technique across different school subjects or even topics within a single subject where *alternative conceptions* are less present. This could even be done concurrently as learners get used to the instructional format using a within subjects design to minimise other factors. As mentioned in the concept knowledge section, examining concept questioning compared with "predict-observe-explain" style tasks (open vs. closed questions) would also allow a comparison that looks at the effects of openness of question, and hence correctness of answer, on the motivational factors as well.

6 Summaries



– Randall Monroe,
xkcd #895: Teaching Physics, xkcd.com/895/,

Chapter Contents

This following section summarises the doctoral thesis for two audiences, researchers and teachers.

6.1 Research Summary

This section gives a summary of the work contained in this thesis for researchers. The summary is presented by chapter, so that readers can refer to each for more detail. Chapter one is omitted as it is a personal motivation. The thesis is concerned with the lower secondary topic of introductory direct current electricity in Year 8 (aged 12-13) learners in the UK. Broken up into chapters that, firstly, review the literature with regards to learner thought on the topic of electricity and how to measure it (Chapter 2). Followed by, a verification process that the testing methods work for the learners participating in the study and how testing materials were adapted to them (Chapter 3). This is then followed by the rationale and process of adapting and re-developing non-digital teaching and learning materials used in previous interventions (used in experimental group 1), as well as, the theory and rationale for developing an accompanying tablet application (used in experimental group 2) (Chapter 4). The concept knowledge and affective changes between these two experimental groups are measured and the resulting data in presented (Chapter 5).

6.1.1 Theory of Measurement of Learning and Knowledge

Chapter 2 presents an overview of relevant learning theories, presenting key ideas from educational psychology. Firstly, I introduce the idea of *mental representations* from Piaget. Importantly, the idea of a *schema* that is a kind of mental image that allows for categorising of objects and the processes that adjust them (*assimilation* and *accommodation*)[443]. These build a fundamental basis for dealing with learning of figurative knowledge. Vygotsky centres the use of social interaction and our main tool for it, language. The key ideas he contributes to the work of this thesis are those of *internalisation*, which can be understood

[443] Piaget [1929]

as the active process of moving information from the outside world into our *mental representations*, and *externalisation*, the opposite. Both processes require active processing and may change learners' internal *mental representations*[444]. The other key idea is that of a *psychological or cultural tool*. These are any symbolic or linguistic representations of ideas[445] and range in this study from diagrams, peer talk, analogies to a tablet application. Vygotsky also defines the idea of the *zone of proximal development*, of what a learner can achieve additionally with an adult or more capable peer compared with alone[446]. This can be achieved through learning guidance referred to by Wood et al. [1976] as *scaffolding*. Rogoff extends this with evidence to show development of new skills supported by symmetrical dyads - pairs of learners where neither is an expert in the task[447]. As the learners are likely of similar ability, this is useful when considering peer talk. Sameroff emphasises the interaction of learner with their environment. Rather than any changes being mono-directional, into the mind of the learner, learners are seen as active participants in their environment[448]. These ideas are developed with reference to teacher feedback mediated by a tablet application and by learners interacting with the application itself.

Beginning with foundational, theoretical works by Kuhn [1962] and Toulmin [1972] that examine how changes occur in scientific thought, I then develop the ideas of learning specific to science and physics. The theories of conceptual change from Posner et al. [1982], McCloskey [1983], Carey [2009], Vosniadou et al. [2008] and Chi [1992] are each briefly described and evaluated. There is a lack of evidence for the first three. Vosniadou et al. [2008] seem to offer only one extra layer of abstraction in accessing a final "Theory-Theory" like construct, as in Carey [2009]. Chi [1992] offers a theory that does not reflect the context specificity of learners' reasoning. These theoretical underpinnings are

[444] Vygotsky [1986]
[445] Vygotsky [1981b]
[446] Vygotsky [1978]
[447] Rogoff [1991]
[448] Sameroff [2009]

therefore foregone in favour of diSessa [1988]. A longer discussion of diSessa's *Knowledge in Pieces* situates the work in its theoretical framing. *Knowledge in Pieces* is statistical and context specific in its nature, meaning ideas can be activated with different triggering possibilities by different cues in the context. The building blocks of these ideas are called *phenomenological primitives* or *p-prims* and are simple, indivisible ideas from everyday life. The evidence for this theory, its context specific nature and the positive framing of learners' prior knowledge, means that this theoretical framing is adopted. Once the physical conception we are teaching has been established, the *alternative conceptions* and implications for practice are discussed, with a thorough review of international literature on the *alternative conceptions* on the subject of electricity present in learners is given. Special attention is paid to the language of origin and how these influence the *alternative conceptions* shown by learners, as this work is concerned with applicability from German to English speaking contexts. All the conceptions found in the literature are categorised and summarised in Table 2.2. Tests used to measure the conceptual understanding of electricity are subsequently presented and evaluated. The choice was made to use and redevelop the test presented in Urban-Woldron and Hopf [2012] as the concept test for this study. This is due to its curriculum relevance for the target group, readability for the target group, psychometric basis for diagnosing *alternative conceptions* and the desire to maintain comparability with previous work carried out in German.

6.1.2 Verifying Testing Materials

Chapter 3 begins by establishing that the test is suitable for the learning outcomes as defined in the National Curriculum for England[449]. As the Urban-Woldron and Hopf [2012] test is originally in German and must be translated into English for the study, norms and good practice for translations are established inline with ISO17100. Translation of the test text was carried out to these standards. To ensure validity and barrier-free nature of the materials a *cognitive laboratory interview*

449 Department for Education [2014]

study was carried out, examining the research questions: TA-RQ1) Do the learners' spoken explanations match coded *alternative conceptions* from their written answers? and TA-RQ2) Are an adequate number of *alternative conceptions* coded? Testing materials were apportioned into three test packs[450], smaller than the whole test so that learners did not get as fatigued when talking through their reasoning. A total of 31 interviews (averaging around 14 minutes in length) were conducted with learners both pre- and post-instruction from the ages of 11-14. Interviews were transcribed and then coded in a first pass using the *alternative conceptions* coded in the original Urban-Woldron test. Then on a second pass with a larger range of possible alternative conceptions from the wider literature presented in the previous chapter, as well as, inductively from the arguments learners made. Examples of interview responses are presented that show typical response patterns to questions. These often present more than one *alternative conception* or general difficulty within a single answer. It is then discussed how the codes of singular utterances are then developed into a *summative code*, containing all present non-mutually exclusive or refuted codes. These *summative codes* are then summarised numerically and taken as partial support for an adequate number of *alternative conceptions* being encoded in answer to TA-RQ2.

The list of codes with examples and discussion is then provided to evidence the analysis undertaken. These show among the *alternative conceptions* not diagnosed by the test, *alternative conceptions* novel to the literature. Notable among them is the quite common *Resistor as Power-Source* conception. Co-occurrences of spoken and written codes are then examined, tested with Cohen's Kappa revealing "moderate" agreement and therefore establishing a partially positive answer to TA-RQ2. Novelly, problems that learners have with parallel circuits are then deconstructed on the basis of interview responses and the results are presented ready to be integrated into question responses later in the chapter.

[450] Shown in Appendix A.

The methodology is critiqued with regards to the high proportion of vague (11%) and non-reasoned (13%) responses learners give, due to the lack of follow up questioning. Ultimately, this is accepted to minimise learners' reactivity to the interviewer. The interview responses are then analysed with respect to usability, looking at: TA-RQ3) What features of the questions are barriers to learners' understanding of what is being asked? TA-RQ4) Are there any features acting as unintended distractors? Barriers and unintended distractors (reading of units, filling out numerical answers and grids on diagrams) were identified for removal in the final version of the test. Building on the interviews, answer combinations for diagnosis of additional *alternative conceptions* were added to the questions. Care was taken to add these across contexts, with minimal additional tiers needed. The additional *alternative conceptions* measured by the redeveloped test are: *Resistors as a Power-Source*, *Giving-Taking-Requiring* and *Current-Distance*. The Urban-Woldron and Hopf [2012] test measures any incorrect answer on parallel circuits as one *alternative conception*. This is subdivided into more specific difficulties: *Parallel Opposite Confusion* and the *Geometrically Parallel Confusion*.

The versions of the concept test are analysed using statistical methods and compared with other tests on electricity. The redeveloped test is shown to have acceptable internal consistency[451], with the redeveloped test marks having a significantly improved internal consistency than if marked with the old testing rubric. This again is true for the subscale for learners examining the relationship between current and resistance. No other sub-scale reaches an acceptable α_{Cronbach}.

Rasch analysis shows the test to be too difficult for the target learners and unable to be Rasch scaled. It is called into question as to whether it is possible to have a test where answers are based on highly co-correlating *alternative conceptions* and for it to be truly unidimensional and have invariant difficulties across ability groupings.

[451] Taber [2018b]

Confirmatory Factor Analyses for each of the measured *alternative conceptions* show only one scale with all factors loading well, *Parallel Opposite Confusion*. Future work may consider a multi-dimensional model, reflecting the context specificity. Factors that may be context triggers for learners on the basis of these results include:

- Addition vs. exchange of components,
- Use of light bulbs vs resistors vs other components,
- Inclusion of rote learnt phrases,
- Use of fixed vs variable resistors,
- Technical vs physical current,
- Parallel, series and short circuits.

6.1.3 Constructing Materials for Learning

Chapter 4 starts with an overview of the concepts in the "Electron Gas" model of teaching electricity from Burde [2018]. Theories about instructional design follow. Through these I build upon Vygotsky's idea of a *psychological or cultural tool* and begin to unpick how to design them to positively influence learner thinking. This is discussed either through what can be done with them, *affordances*, or their limits, *constraints*. The Cognitive Theory of Multimedia Learning[452] is briefly introduced, as principles from it are used throughout the chapter to reflect on material design. The reasons for the success of the intervention in Burde [2018] are reflected on in light of theory. Particular interest is paid to the way the central analogy of *electric pressure* is portrayed both pictorially and through the bridging vocabulary used. Drawing on this background, I explain the rationale for adapting materials for the context of KS3 electricity in UK comprehensive schools and present these as used in experimental group 1. The adaptation is done primarily at the level of linguistic complexity. A complete rewrite of the materials was undertaken and the reading age was reduced from the original text and difficult to comprehend vocabulary removed. In order to identify rare (and therefore potentially challenging) words inline with learner vocabulary estimates, a python script was developed and is available for

[452] Mayer [2005]

use as a Python application that generates vocabulary lists for teachers. The second half of the chapter begins by exploring the evidence for the learning gains shown by the inclusion of collaborative tasks in science education[453]. The seven principles of effective collaborative task design[454] are then introduced and used as a reference throughout the development of the tablet application used in experimental group 2. These are:

Feature 1 Becoming aware of one's own conceptions.
Feature 2 Externalising individual ideas.
Feature 3 Initiating comparable situation models.
Feature 4 Ensure active involvement for all.
Feature 5 Offering each learner opportunities to reflect on each other's conceptual understanding.
Feature 6 Integrating decision-making processes.
Feature 7 Offering the teacher measures to monitor the learning process.

Each of these principles are integrated into a novel iPad application that scaffolds learner-learner talk, used in 5 of the 10 lessons in experimental group 2. This is used along side a booklet based on materials for experimental group 1, to form the materials used in experimental group 2. These two experimental groups form the basis of a comparative study conducted in the winter terms of 2021-22 and 2022-23, respectively. Learning gains were measured using the test redeveloped in the previous chapter, administered pre and post. Three motivational scales were measured, using the Intrinsic Motivation Inventory[455], examining learners' *Interest and Enjoyment*, *Perceived Competence* and *Pressure Felt* in two different contexts: *My Physics Lessons* and *Talking about Science*. These are used to investigate the following research questions:

RQ1: Are learning gains increased through the use of this Computer Supported Collaborative Method?
RQ2: Are aspects of student motivation regarding learners' "physics

[453] Tenenbaum et al. [2019], Jay et al. [2017], Crouch and Mazur [2001], Karabulut-Ilgu et al. [2018]
[454] Heeg et al. [2020]
[455] Ryan and Deci [2000]

lessons" increased through the use of this Computer Supported Collaborative Method?

RQ3: Are aspects of student motivation regarding "talking about science" increased through the use of this Computer Supported Collaborative Method?

Hypothesis H1, formulated with reference to studies discussed earlier in the chapter:
H1: Learning gains for EG2 will be higher than for EG1.

As learners show a desire for more discussion or collaboration in their science lessons[456] and as there are many examples of computerised methods increasing motivation[457], I expect all sub-scales of the IMI to improve. Listed as separate hypotheses:
H2a: *Interest and Enjoyment* gains for EG2 will be higher than for EG1.
H2b: *Perceived Competence* gains for EG2 will be higher than for EG1.
H2c: *Felt Pressure* gains for EG2 will be lower than for EG1.

There is little data to make hypotheses for RQ3, so it is examined exploratively.

6.1.4 Results of the Quasi-Experimental Study

Chapter 5 analyses the data collected in order to show that the use of a computer supported collaborative learning tablet application for scaffolding peer talk was unable to increase the concept related learning outcomes ($N = 228$, $p = 0.0798$, apparent non-significant worsening in learning gains from EG1 to EG2).

The conditions to measure this were not ideal. Due to effects of the COVID-19 pandemic and staffing issues in partner schools, all but one school withdrew from the project. Also due to COVID-19 related issues questionnaires had to be taken using a mixture of media (electronically

[456] Juuti et al. [2010], Teppo et al. [2021]
[457] C.f. Treagust and Tsui [2014].

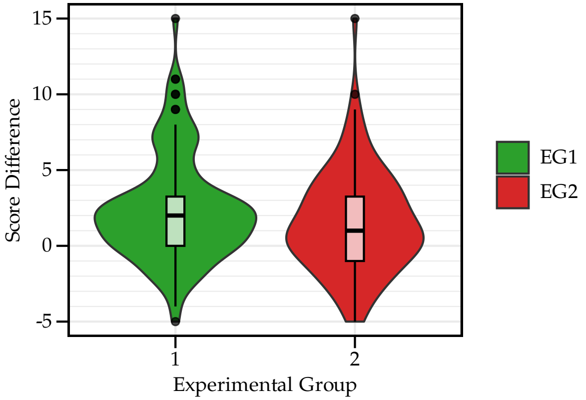


Figure 6.1: Violin with Overlaid Box-and-Whisker Plots Showing Score Differences for Both Experimental Groups. Duplicated from Figure 5.3.

and on paper), impacting comparability and likely the primary factor in the score difference.

Significant changes in sub-scales of the intrinsic motivation inventory revealed, firstly, that learners had significantly less perceived self competence after using the tablet application in their lessons ($N = 218$, $p = 0.00781$). This may have been due to a similar effect to Dreyfus et al. [1990], who observe in cognitive conflict interventions, that weaker prior attaining learners develop negative attitudes towards school. And secondly, that learners show significantly less interest in talking about science ($N = 209$, $p = 0.00860$) after the talk based intervention. This could possibly be due to the fact that learners were not used to talk as a method of learning and begin associating it with school for the first time through the intervention.

To summarise, it would seem that scaffolding through a tablet application is unable to substitute for literature based success criteria of: a) a longer intervention, b) explicit talk lessons and c) teacher training, present in other studies[458]. The lack of these in my study is due to multiple reasons:

- The intervention here was carried out in a short time, a 10 lesson block.
- Constrained by secondary science curriculum not allowing time for "talk lessons".
- The constraints of the project not allowing time or resources for teacher CPD, being a one man team and at a distance.

However, further questions are: the appropriateness of the technique to lower secondary and whether the nature of physics, as a subject fraught with *alternative conceptions*, cognitive conflict and closed questioning, is the right context for such an intervention.

Future work could integrate such a tablet application into classrooms where the teacher (or the class) are already familiar and practised with peer-talk. A longitudinal study could consider the effectiveness of additional scaffolding on reducing transition times into the talk activities. A study could also look at modifying the tasks set as a talk activity, varying the form from closed to open and examining the effects of that on both attainment and motivation. The change over time of learners' motivation could also be investigated, to explore how the change in expectations from written to spoken work varies over time.

6.1.5 Closing Remarks

It is clear that with the dynamic nature and context specificity of learning that the following quotation from Bruner [1977, p. 32] rings as true as ever:

> What is abundantly clear is that much work remains to be done by way of examining currently effective practices, fashioning curricula that may be tried out on an experimental basis, and carrying out the kinds of research that can give support and guidance to the general effort at improving teaching.

[458] Mercer et al. [2004], Hanley et al. [2015]

What was able to be developed in this thesis is a good quality set of materials matched to the National Curriculum for England provided free of charge to teachers. A Proof-of-Concept tablet application was developed and successfully implemented in a school setting. It was also possible to show that learning outcomes were positive with a medium effect strength across both groups. Novel *alternative conceptions* were seen in the learners in the *cognitive laboratory interviews* and a new categorisation of the difficulties of understanding parallel circuits was developed, the first in the literature.

The intervention also drew attention to the success factors of talk based interventions in school, that the scaffolding provided by the application was not able to replicate. Peculiarities of the types of tasks set in physics and the difficulties of making effective talk tasks out of them became apparent. Specifically, the intersection of *alternative conceptions*, *cognitive conflict*, open-vs-closed answers and motivation, that seem to underpin the differences in the interventions in the literature.

Although no flagship, big effect intervention was identifiable, these steps provide strengthening evidence for what is needed for a successful talk-based intervention and a solid foundation for those looking to develop and test one on the subject of electricity.

6.2 *Teacher Summary*

The focus of teachers will differ from that of the research staff looking to gain from reading this work. For this reason, the following section will summarise the useful aspects of this work as they relate to teaching practice.

6.2.1 *Alternative Conceptions about Electricity*

Learners often do not think about electricity as being differentiated into current, voltage, charge, power or energy. Instead they *cluster* these all together in a nebulous blob of things that they might even avoid naming! There are a few key words they often associate with this nebulous electricity: electricity (or one of the subject specific vocabulary) can be used, shared or maybe halved. You might wish to avoid using these words as they may just reinforce previous misunderstandings.

Initially, learners may think that electricity only needs one wire to get from its source (a battery) to the bulb (a consumer), but quickly learn the rule that a circuit must be closed. Internalisation of this rule however does not supplant the idea that current gets used up! When asked what the other wire is doing it might be providing more electricity to the bulb or even just there as a safety feature.

This brings us to our post teaching general difficulty: learners will often learn a rule and apply it everywhere. If they learnt "current is constant in a series circuit", it may be applied with voltage instead of current and in all circuits instead of just series circuits. We can see two things on display here:

- "Constant" is the word that sticks out to learners, and not the two other key parts "current" and "series" with which they may be unfamiliar.
- Learning of such declarative statements is not indicative of real cognitive change or deep learning.

Furthermore, the battery may be seen as a constant current source, not a constant voltage source. Hence, I would encourage the use of the word *voltage source* - and definitely not power source - when you're teaching.

Voltage is a tricky concept to teach. It is a difference in potential, i.e. you need to refer to two points in a circuit to be able to speak about it, unlike current. This comparative nature makes it difficult for learners who often see it as a property of the current, maybe its strength, if they even differentiate it from current at all. However, it is justified that learners often equate no current with no voltage. You will see later how this syllabus centres voltage as a core concept and cause of current to give it the attention it needs for understanding it, rather than the afterthought it often is.

Resistance may be seen as a consumer rather than a hemmer of flow. Although the idea that a longer resistor provides more resistance seems to be easily understood, learners believe that a (bigger) component with a higher cross-sectional surface area provides more resistance, possibly related to a bigger consumer using more electricity.

An open switch is not an open door, so learners may see an open switch as letting electricity through. They may also see the open switch as "breaking" the whole circuit and stopping flow throughout it all, not just at the branch with the switch.

Learners have problems identifying parallel circuits: they look for parallel lines instead of parallel branches and confuse parallel and series as well as parallel and perpendicular.

Learners also tend to argue from the "point of view" of the current as they analyse a circuit. This shows itself in two ways. Firstly, they will argue sequentially as if they are an electron (or positive charge) going through the circuit and meet each component. Secondly, they may also pick points on the circuit, such as a branch, and without considering the rest of the circuit as a whole, argue locally. In this case, that the current splits 50:50 along the branches, without considering the voltage and resistance along those branches.

All of these alternative conceptions are very stubborn and are not easily addressed. They are built on structures and ideas useful for everyday life, that serve in ordinary situations, so do not be disheartened if your learners are not arguing scientifically or even seem to be regressing.

6.2.2 Materials for Your Classroom

All resulting materials (a text book, slides, a teaching guide and worksheets) were provided to teachers and learners. These formed the basis of experimental group 1 (EG1). The materials and a brief teacher-friendly explainer can be found here, Figure 6.2. The resource pack is a locked zip file the password to which can be obtained by emailing me at weatherby@physik.uni-frankfurt.de.

Figure 6.2: QR Code for the book and resource pack used for experimental group 1.

This, alongside a booklet following the course, outlined previously in Section 4.1.2, formed the basis for the materials used with experimental group 2 (EG2). The booklet includes sections on static electricity and magnetism too, in order to contain all the content required by the National Curriculum for Electricity and Magnetism more widely and is available here, Figure 6.3. Other topics did not form part of the intervention and were taught before or after the topics under investigation.

Figure 6.3: QR Code for the booklet used for experimental group 2.

6.2.3 *Key Takeaways*

- If you wish to embed collaborative talk in your practice ensure you receive high-quality CPD before doing so.
- Explicitly instruct your learners on how to engage in productive talk, using these Ground Rules.[459]
- Practise talking routines and embed over a long time scale.
- Try using more open questions for discussion tasks.

[459] Mercer's Ground rules for Exploratory Talk.

A Testing Materials

A.1 Testing Materials used in Cognitive Laboratory Interview

Questions here are used to verify the testing materials and split into three “Question Packs” that were used in cognitive laboratory interviews where learners discuss their reasoning for each question. These questions were then redeveloped into the test used in the intervention printed in Appendix A.2. Questions are marked with “`DRAFT`” as they were not distributed for automated scanning.

A.1.1 Question Pack 1

DRAFT

evasys	Electricity Thinking Aloud - Question Pack 1	evasys

Goethe-Universität, Frankfurt am Main — Thomas Weatherby
Department of Physics Education — Question Pack 1

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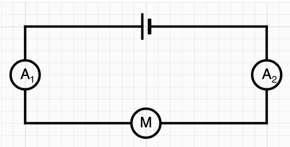
Correction: ☐ ■ ☐ ☒ ☐ Please follow the examples shown on the left hand side to help optimize the reading results.

1. Item 4

1.1 In the circuit on the right, there is a battery connected to a motor.

What can we say about the measurements on both the Ammeters?

- ☐ A_1 shows a higher current.
- ☐ Both Ammeters show the same current.
- ☐ A_2 shows a higher current.

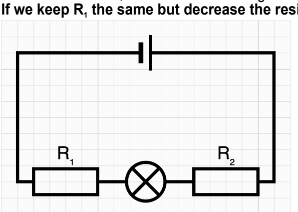


1.2 **Give a reason for your answer.**

- ☐ The current is the same in the whole circuit.
- ☐ Some of the current gets used up in the motor.
- ☐ All of the current gets used up in the motor.

2. Item 15

2.1 In the circuit below, two resistors and a light bulb are connected to a battery.
If we keep R_1 the same but decrease the resistance of R_2, what happens to the brightness of the light bulb?



- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb gets dimmer.

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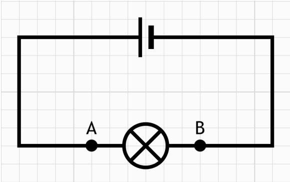
3. Item 22

3.1 The light bulb in the circuit below is glowing.
What can we say about the current at points A and B?



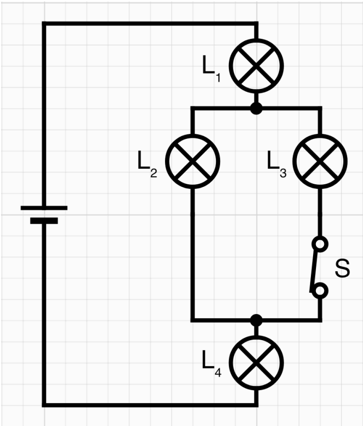
- ☐ The current is bigger at A than B.
- ☐ The current is bigger at B than A.
- ☐ The current is the same at A and B.

3.2 **Give a reason for you answer.**

- ☐ The current is the same in the whole circuit.
- ☐ Some of the current gets used up in the light bulb.
- ☐ All of the current gets used up in the light bulb.

4. Item 7

4.1



In the circuit on the left, there are four identical light bulbs connected to a battery. The switch S is closed to begin with, as in the diagram.
What happens to the current through the light bulb L_2, when we open the switch?

- ☐ The current through L_2 gets bigger.
- ☐ The current through L_2 stays the same.
- ☐ The current through L_2 gets smaller.
- ☐ More information is needed to answer this question.

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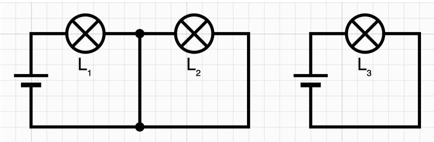
5. Item 24

5.1 Compare the brightness of the light bulbs L_1, L_2 and L_3 in both circuits.
Which light bulbs are the brightest?



- ☐ Light bulb L_1 glows the brightest.
- ☐ Light bulb L_2 glows the brightest.
- ☐ Light bulb L_3 glows the brightest.
- ☐ Light bulbs L_1 and L_2 glow the brightest.
- ☐ Light bulbs L_1 and L_3 glow the brightest.

6. Item 16

The light bulbs in the picture are all the same. The total current is 1.2 A.
Write the missing currents for each of the branches I_1, I_2 and I_3.

6.1 Current I_1 =

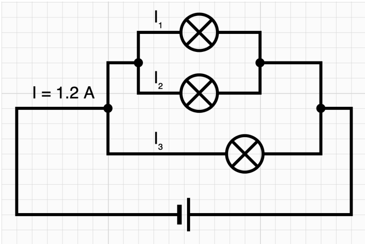
☐☐.☐☐ A

6.2 Current I_2 =

☐☐.☐☐ A

6.3 Current I_3 =

☐☐.☐☐ A



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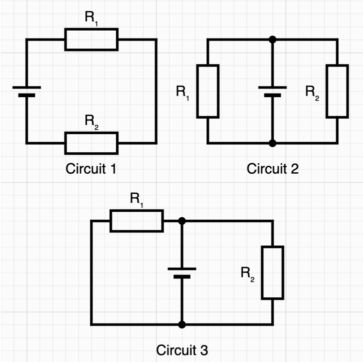
evasys	Electricity Thinking Aloud - Question Pack 1	evasys

7. Item 9

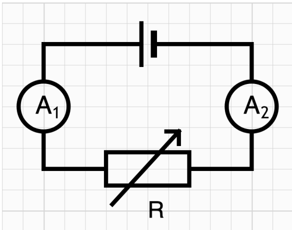
7.1 **In which of the circuits are R_1 and R_2 connected in parallel to the battery?**



- ☐ Circuits 1, 2 and 3
- ☐ Circuit 2
- ☐ Circuit 1
- ☐ Circuits 1 and 2
- ☐ Circuits 2 and 3

8. Item 27

The circuit on the right is built from two ammeters and a variable resistor.
Both ammeters show us the current.
Now we increase the resistance R.



8.1 **What happens to the current at ammeter A_1?**
☐ It gets bigger. ☐ It stays the same.
☐ It gets smaller.

8.2 **What happens to the current at ammeter A_2?**
☐ It gets bigger. ☐ It stays the same.
☐ It gets smaller.

8.3 **Give a reason for your answers.**
- ☐ A larger resistance needs more current than a smaller resistance.
- ☐ It is the same battery, so is gives the same current.
- ☐ A larger resistance means a smaller current everywhere in the circuit.
- ☐ A larger resistance means a smaller current after the resistance. So, the current before the resistor does not change.
- ☐ A larger resistance means a smaller current after the resistance. So, the current before the resistor gets bigger.

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9. Item 31

Look at the following circuit.
How high is the voltage (potential difference):

9.1 Between points 1 and 2:

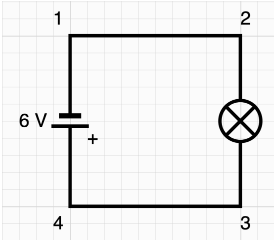
__ __ . __ __ V

9.2 Between points 2 and 3:

__ __ . __ __ V

9.3 Between points 3 and 4:

__ __ . __ __ V



We now put another of the same light bulbs between point 3 and 4.
How high is the voltage in the circuit with two light bulbs:

9.4 Between points 1 and 2:

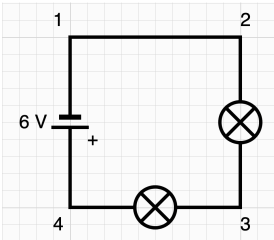
__ __ . __ __ V

9.5 Between points 2 and 3:

__ __ . __ __ V

9.6 Between points 3 and 4:

__ __ . __ __ V



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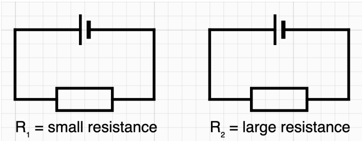
10. Item 3

10.1 The resistor R_1 in a circuit (shown on the left) has a small resistance. We swap that resistor with a resistor R_2 with a higher resistance (shown on the right).
What happens to the current in the circuit?



- ☐ It gets bigger.
- ☐ It gets smaller, but not to zero.
- ☐ It stays the same.
- ☐ No current flows.

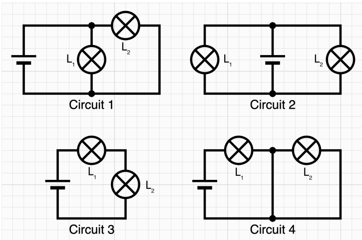
10.2 **Give a reason for your answer.**

- ☐ The battery is not strong enough to get any current through the bigger resistance.
- ☐ The battery cannot push as much current as before through the bigger resistance.
- ☐ The bigger resistance needs more current than a smaller resistance.
- ☐ It is the same battery, so the current remains the same.

11. Item 20

11.1 **In which circuits (on the right) are the light bulbs L_1 and L_2 connected in parallel to the battery?**

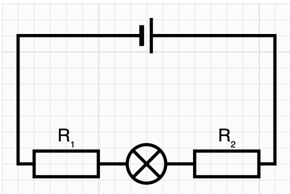
- ☐ Circuit 1
- ☐ Circuit 2
- ☐ Circuit 3
- ☐ Circuits 1 and 2
- ☐ Circuits 1, 2 and 4



12. Item 25

12.1 In the circuit to the right two resistors and a light bulb are connected to a battery.
If we keep R_1 the same and increase the resistance of R_2, what happens to the brightness of the light bulb?

- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb gets dimmer.



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A.1.2 Question Pack 2

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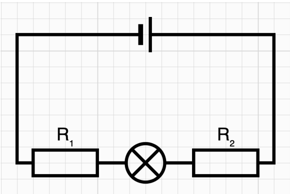
Goethe-Universität, Frankfurt am Main — Thomas Weatherby
Department of Physics Education — Question Pack 2

Mark as shown: ☐ ☒ ☐ ☐ ☐ Please use a ball-point pen or a thin felt tip. This form will be processed automatically.
Correction: ☐ ■ ☐ ☒ ☐ Please follow the examples shown on the left hand side to help optimize the reading results.

1. Item 10

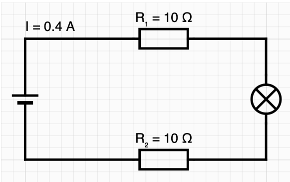
1.1 In this circuit there are two resistors and a light bulb connected to a battery.
If we keep R_2 the same but decrease the resistance of R_1, what happens to the brightness of the light bulb?



- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb gets dimmer.

2. Item 13

2.1 In a circuit with a light bulb and two resistors with resistances $R_1 = 10\ \Omega$ and $R_2 = 10\ \Omega$, there is a current $I = 0.4$ A. The **resistor R_2** is swapped for a resistor with $R_3 = 20\ \Omega$.
What happens to the current through the light bulb?



- ☐ The current is now smaller than 0.4 A.
- ☐ The current is the same as before.
- ☐ The current is now larger than 0.4 A.

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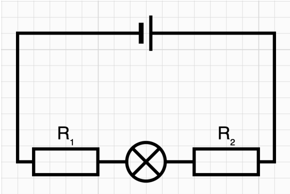
3. Item 29

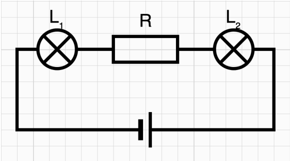
3.1 In the circuit below two resistors and a light bulb are connected to a battery.
If we keep R_2 the same but increase the resistance of R_1, what happens to the brightness of the light bulb?



- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb gets dimmer.

4. Item 26

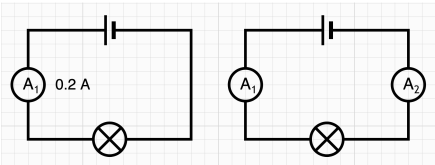
4.1 In the circuit below both light bulbs L_1 and L_2 glow with the same brightness.
What happens to the brightness of both light bulbs if we increase the resistance R?



- ☐ L_1 stays the same. L_2 gets dimmer.
- ☐ L_1 gets dimmer. L_2 stays the same.
- ☐ L_1 and L_2 both get brighter.
- ☐ L_1 and L_2 both get dimmer.
- ☐ L_1 and L_2 both stay the same.

5. Item 28

5.1 In the circuit below the light bulb glows and the ammeter shows a current of 0.2 A.
Now we put in a second Ammeter A_2 on the other side of the circuit.
What current does the ammeter A_2 show?



- ☐ More than 0.2 A.
- ☐ Exactly 0.2 A.
- ☐ Less than 0.2 A, but not 0 A.
- ☐ 0 A.

5.2 **Give a reason for your answer.**
- ☐ The current is the same in the whole circuit.
- ☐ Some of the current gets used up in the light bulb.
- ☐ All of the current gets used up in the light bulb.

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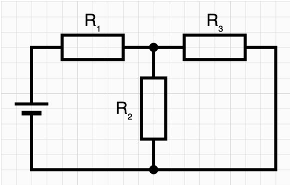
6. Item 14

6.1 Which resistors are connected in **parallel** to each other?

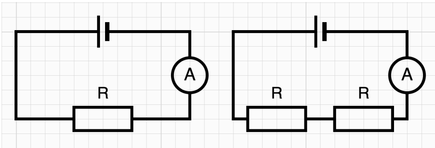
- ☐ R_1 and R_2.
- ☐ R_1 and R_3.
- ☐ None of the resistors are parallel to another.
- ☐ R_2 and R_3.



7. Item 23

7.1 A circuit is built from a battery, a resistor and an ammeter. The Ammeter shows us the current.
What happens to the current on the Ammeter, when we add a second identical resistor R?

- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller, but not zero.
- ☐ No current flows.



7.2 **Give a reason for your answer.**

- ☐ Two resistors need more current than one.
- ☐ The battery cannot push as much current as before through both the resistors.
- ☐ It is the same battery, so the current remains the same.
- ☐ The battery is not strong enough to get any current through both resistors.
- ☐ The current is shared over both resistors, so it is halved.

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8. Item 32

The following circuit is made from two identical light bulbs and a closed switch.
How high is the voltage (potential difference):

8.1 Between points 1 and 2:

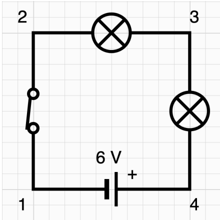
☐☐.☐☐ V

8.2 Between points 2 and 3:

☐☐.☐☐ V

8.3 Between points 3 and 4:

☐☐.☐☐ V



Now we open the switch between points 1 and 2.
How high is the voltage (potential difference):

8.4 Between points 1 and 2:

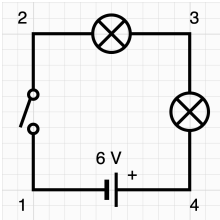
☐☐.☐☐ V

8.5 Between points 2 and 3:

☐☐.☐☐ V

8.6 Between points 3 and 4:

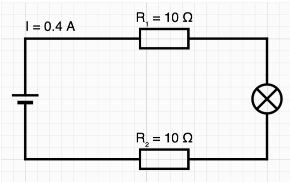
☐☐.☐☐ V



9. Item 2

9.1 In a circuit with a light bulb and two resistors with resistances $R_1 = 10\ \Omega$ and $R_2 = 10\ \Omega$ there is a current $I = 0.4$ A. The **resistor R_1** is swapped for a resistor with $R_3 = 20\ \Omega$.
How does this change the current through the light bulb?

- ☐ The current is bigger than 0.4 A.
- ☐ The current is the same as before.
- ☐ The current is smaller than 0.4 A.



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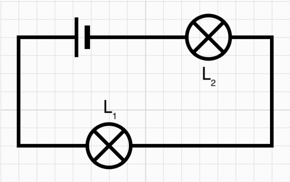
10. Item 21

10.1 Look at the circuit on the right.
How bright do the light bulbs glow?



- ☐ Both light bulbs glow. L_1 glows brighter than L_2.
- ☐ Both light bulbs glow. L_2 glows brighter than L_1.
- ☐ Both light bulbs glow with the same brightness.
- ☐ L_1 glows. L_2 does not.
- ☐ L_2 glows. L_1 does not.

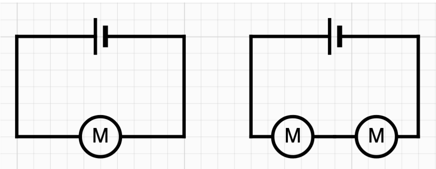
10.2 **Give a reason for your answer.**

- ☐ L_1 uses up all the current. There is no more current left for L_2.
- ☐ The current is shared between both light bulbs evenly.
- ☐ L_1 uses up some of the current. So, there is less current left for L_2.
- ☐ L_2 is closer to the battery. So, it gets more current.
- ☐ The current is the same in the whole circuit.

11. Item 6

11.1 A circuit is made from a battery and a motor. The motor is running (shown on the left). Then we add a second motor (shown on the right).

What happens to current in the circuit?



- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller, but not to zero.
- ☐ No current flows.

11.2 **Give a reason for your answer.**

- ☐ The battery is not strong enough to get any current through both motors.
- ☐ Two motors need more current than one.
- ☐ It is the same battery, so the current stays the same.
- ☐ The current is shared over both motors, so it is halved.
- ☐ The battery cannot push as much current as before through both the motors.

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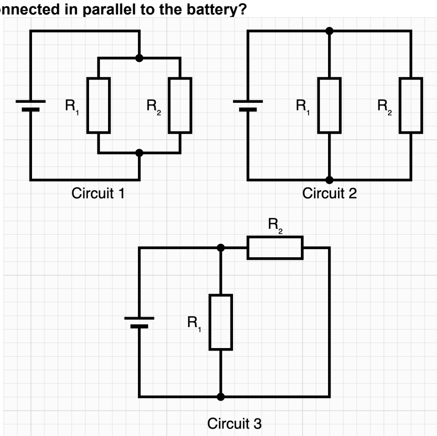
evasys	Electricity Thinking Aloud - Question Pack 2	evasys

12. Item 30

12.1 **In which of the circuits are R_1 and R_2 connected in parallel to the battery?**

- ☐ Circuits 1, 2 and 3
- ☐ Circuit 2
- ☐ Circuit 1
- ☐ Circuits 1 and 2
- ☐ Circuits 2 and 3



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A.1.3 Question Pack 3

DRAFT

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Goethe-Universität, Frankfurt am Main
Department of Physics Education

Thomas Weatherby
Question Pack 3

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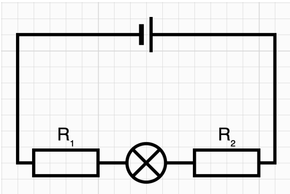
Correction: ☐ ■ ☐ ☒ ☐ Please follow the examples shown on the left hand side to help optimize the reading results.

1. Item 25

1.1 In the circuit to the right two resistors and a light bulb are connected to a battery.
If we keep R_1 the same and increase the resistance of R_2, what happens to the brightness of the light bulb?

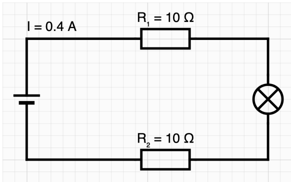
- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb gets dimmer.



2. Item 2

2.1 In a circuit with a light bulb and two resistors with resistances R_1 = 10 Ω and R_2 = 10 Ω there is a current I = 0.4 A. The **resistor R_1** is swapped for a resistor with R_3 = 20 Ω.
How does this change the current through the light bulb?

- ☐ The current is bigger than 0.4 A.
- ☐ The current is the same as before.
- ☐ The current is smaller than 0.4 A.



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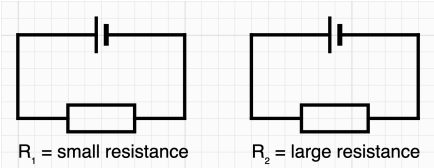
3. Item 3

3.1 The resistor R_1 in a circuit (shown on the left) has a small resistance. We swap that resistor with a resistor R_2 with a higher resistance (shown on the right).

What happens to the current in the circuit?



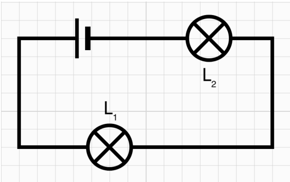
- ☐ It gets bigger.
- ☐ It gets smaller, but not to zero.
- ☐ It stays the same.
- ☐ No current flows.

3.2 **Give a reason for your answer.**

- ☐ The battery is not strong enough to get any current through the bigger resistance.
- ☐ The battery cannot push as much current as before through the bigger resistance.
- ☐ The bigger resistance needs more current than a smaller resistance.
- ☐ It is the same battery, so the current remains the same.

4. Item 21

4.1 Look at the circuit on the right.
How bright do the light bulbs glow?



- ☐ Both light bulbs glow. L_1 glows brighter than L_2.
- ☐ Both light bulbs glow. L_2 glows brighter than L_1.
- ☐ Both light bulbs glow with the same brightness.
- ☐ L_1 glows. L_2 does not.
- ☐ L_2 glows. L_1 does not.

4.2 **Give a reason for your answer.**

- ☐ L_1 uses up all the current. There is no more current left for L_2.
- ☐ L_1 uses up some of the current. So, there is less current left for L_2.
- ☐ The current is the same in the whole circuit.
- ☐ The current is shared between both light bulbs evenly.
- ☐ L_2 is closer to the battery. So, it gets more current.

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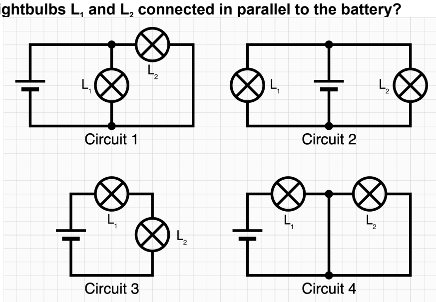
5. Item 20

5.1 **In which circuits (on the right) are the lightbulbs L_1 and L_2 connected in parallel to the battery?**

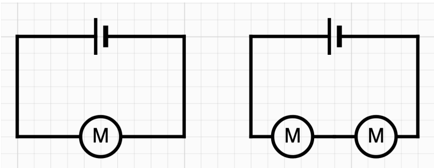
- ☐ Circuit 1
- ☐ Circuit 2
- ☐ Circuit 3
- ☐ Circuits 1 and 2
- ☐ Circuits 1, 2 and 4



6. Item 6

6.1 A circuit is made from a battery and a motor. The motor is running (shown on the left). Then we add a second motor (shown on the right).

What happens to current in the circuit?



- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller, but not to zero.
- ☐ No current flows.

6.2 **Give a reason for your answer.**

- ☐ The battery is not strong enough to get any current through both motors.
- ☐ It is the same battery, so the current stays the same.
- ☐ The battery cannot push as much current as before through both the motors.
- ☐ Two motors need more current than one.
- ☐ The current is shared over both motors, so it is halved.

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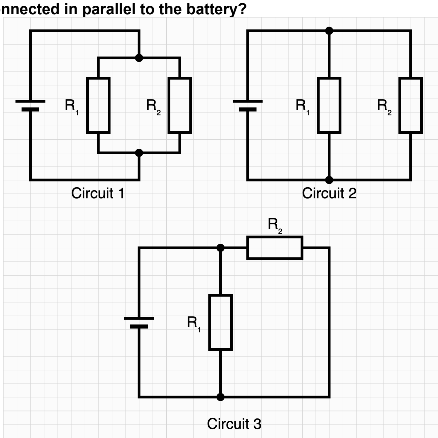
7. Item 30

7.1 **In which of the circuits are R_1 and R_2 connected in parallel to the battery?**

- ☐ Circuits 1, 2 and 3
- ☐ Circuit 2
- ☐ Circuit 1
- ☐ Circuits 1 and 2
- ☐ Circuits 2 and 3



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8. Item 31

Look at the following circuit.
How high is the voltage (potential difference):

8.1 Between points 1 and 2:

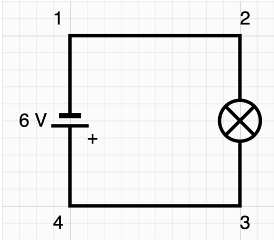
☐☐.☐☐ V

8.2 Between points 2 and 3:

☐☐.☐☐ V

8.3 Between points 3 and 4:

☐☐.☐☐ V



We now put another of the same light bulbs between point 3 and 4.
How high is the voltage in the circuit with two light bulbs:

8.4 Between points 1 and 2:

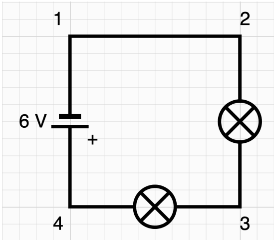
☐☐.☐☐ V

8.5 Between points 2 and 3:

☐☐.☐☐ V

8.6 Between points 3 and 4:

☐☐.☐☐ V

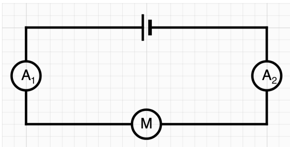


9. Item 4

9.1 In the circuit on the right, there is a battery connected to a motor.

What can we say about the measurements on both the Ammeters?

- ☐ A_1 shows a higher current.
- ☐ Both Ammeters show the same current.
- ☐ A_2 shows a higher current.



9.2 **Give a reason for your answer.**

☐ The current is the same in the whole circuit. ☐ Some of the current gets used up in the motor. ☐ All of the current gets used up in the motor.

F25610U0P5PL0V0 28.04.2021, Page 5/6

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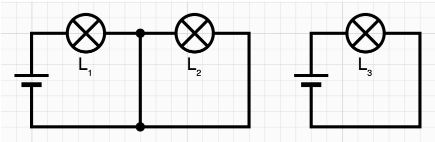
10. Item 24

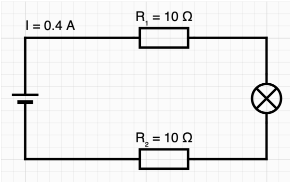
10.1 Compare the brightness of the light bulbs L_1, L_2 and L_3 in both circuits (see diagram).
Which of the light bulbs glow the brightest?



- ☐ Light bulb L_1 glows the brightest.
- ☐ Light bulb L_2 glows the brightest.
- ☐ Light bulb L_3 glows the brightest.
- ☐ Light bulbs L_1 and L_2 glow the brightest.
- ☐ Light bulbs L_1 and L_3 glow the brightest.

11. Item 13

11.1 In a circuit with a light bulb and two resistors with resistances R_1 = 10 Ω and R_2 = 10 Ω there is a current I = 0.4 A. The **resistor R_2** is swapped for a resistor with R_3 = 20 Ω.
What happens to the current through the light bulb?

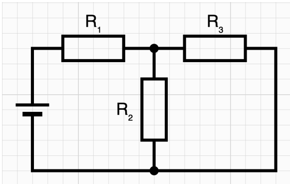


- ☐ The current is now smaller than 0.4 A.
- ☐ The current is the same as before.
- ☐ The current is now larger than 0.4 A.

12. Item 14

12.1 Which resistors are connected in **parallel** to each other?

- ☐ R_1 and R_2.
- ☐ R_1 and R_3.
- ☐ None of the resistors are parallel to another.
- ☐ R_2 and R_3.



A.2 Redeveloped Tests Used in the Intervention

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Goethe-Universität, Frankfurt am Main **Thomas Weatherby**

Department of Physics Education **POST**

Mark as shown: ☐ ☒ ☐ ☐ ☐ **Please use a ball-point pen or a thin felt tip. This form will be processed automatically.**

Correction: ☐ ■ ☐ ☒ ☐ **Please follow the examples shown on the left hand side to help optimize the reading results.**

1. Introduction

Hello everyone!
My name is Tom and it's my job to try and make science lessons better. I hope you enjoyed your lessons on electricity. I'm asking you to fill out this questionnaire as it will help me know how much you've learnt in the past few weeks. Please try your best to answer **every question as best as you can**. Even if you don't know the answer it's really helpful to know how you think!
Thank you very much for your help,
Thomas Weatherby

2. About You

2.1 Your Gender ☐ Male ☐ Female ☐ Non-Binary ☐ Prefer to Self-Describe

2.2 If you chose to self-describe, please do so here:

[ ]

How to make your code:
- Take the day of your birthday and put it in the first two boxes.
- Take the first two letters of your Mum's or female guardian's name in the second and third box, if you don't have a female guardian put XX.
- Take the first two letters of your Dad's or male guardian's name in the fourth and fifth box, if you don't have a male guardian put XX.
In the example, the student is born on the 9th of May (09), their Mum is called Shirley (SH) and their Dad is called Ernest (ER).

Example Code:

0 9 S H E R

2.3 Your Code:

☐ ☐ ☐ ☐ ☐ ☐

3. My Physics Lessons

These questions ask how you feel about your in classroom physics (or science) lessons. If you think the statement is **very true** for you, tick the box on the very **right** hand side. If you think the statement is **not at all true** for you, tick the box on the very **left** hand side. Or, you can pick somewhere in the middle.

		Not at all true			Somewhat true			Very true
3.1	I do not feel at all nervous in my physics lessons.	☐	☐	☐	☐	☐	☐	☐
3.2	I think I am pretty good at physics.	☐	☐	☐	☐	☐	☐	☐
3.3	I find physics lessons very interesting.	☐	☐	☐	☐	☐	☐	☐
3.4	I feel tense while in my physics lessons.	☐	☐	☐	☐	☐	☐	☐
3.5	Physics lessons are fun.	☐	☐	☐	☐	☐	☐	☐
3.6	I feel relaxed while in my physics lessons.	☐	☐	☐	☐	☐	☐	☐
3.7	I am satisfied with my performance in my physics lessons.	☐	☐	☐	☐	☐	☐	☐
3.8	I think physics lessons are very boring.	☐	☐	☐	☐	☐	☐	☐
3.9	I feel pretty skilled at physics.	☐	☐	☐	☐	☐	☐	☐
3.10	I feel under pressure while in my physics lessons.	☐	☐	☐	☐	☐	☐	☐
3.11	I would describe my physics lessons as very enjoyable.	☐	☐	☐	☐	☐	☐	☐
3.12	Working in my physics lessons, is something I can't do very well.	☐	☐	☐	☐	☐	☐	☐

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4. Talking About Science

These questions ask how you feel about talking about science. If you think the statement is **very true** for you, tick the box on the very **right** hand side. If you think the statement is **not at all true** for you, tick the box on the very **left** hand side. Or, you can pick somewhere in the middle.

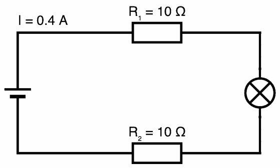
		Not at all true			Somewhat true			Very true
4.1	I do not feel at all nervous when talking about science.	☐	☐	☐	☐	☐	☐	☐
4.2	I think I am pretty good at talking about science.	☐	☐	☐	☐	☐	☐	☐
4.3	I find talking about science very interesting.	☐	☐	☐	☐	☐	☐	☐
4.4	I feel tense while talking about science.	☐	☐	☐	☐	☐	☐	☐
4.5	Talking about science is fun.	☐	☐	☐	☐	☐	☐	☐
4.6	I feel relaxed while talking about science.	☐	☐	☐	☐	☐	☐	☐
4.7	I am satisfied with how I can talk about science.	☐	☐	☐	☐	☐	☐	☐
4.8	I think talking about science is very boring.	☐	☐	☐	☐	☐	☐	☐
4.9	I feel pretty skilled at talking about science.	☐	☐	☐	☐	☐	☐	☐
4.10	I feel under pressure while talking about science.	☐	☐	☐	☐	☐	☐	☐
4.11	I would describe talking about science as very enjoyable.	☐	☐	☐	☐	☐	☐	☐
4.12	Talking about science, is something I can't do very well.	☐	☐	☐	☐	☐	☐	☐

5. Item 2

5.1 A circuit with a light bulb and two resistors with resistances R_1 = 10 Ω (Ohms) and R_2 = 10 Ω (Ohms) has a current I = 0.4 A (Amps). The **resistor R_1** is swapped for a resistor with R_3 = 20 Ω (Ohms).

How does this change the current through the light bulb?

- ☐ The current is smaller than 0.4 A (Amps).
- ☐ The current is the same as before.
- ☐ The current is larger than 0.4 A (Amps).



5.2 Give a reason for your answer.

- ☐ A larger resistor gives more current.
- ☐ More resistance means the current is lower everywhere.
- ☐ Current can reach the light bulb from both sides.
- ☐ The light bulb takes as much current as it needs.
- ☐ Some more current gets used up in the light bulb.

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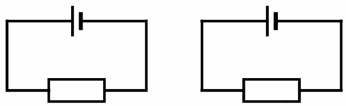
6. Item 3

6.1 The resistor R_1 in a circuit (shown on the left) has a small resistance. We swap that resistor with a resistor R_2 with a higher resistance (shown on the right).

What happens to the current in the circuit?



R_1 = small resistance R_2 = large resistance

☐ It gets bigger.
☐ It gets smaller, but not to zero.
☐ It stays the same.
☐ No current flows.

6.2 **Give a reason for your answer.**

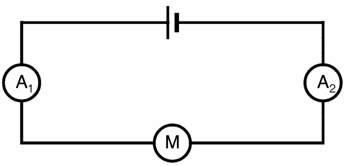
☐ The battery is not strong enough to get the current through the bigger resistor.
☐ The battery cannot push as much current as before through the bigger resistor.
☐ The bigger resistance needs more current than a smaller resistance.
☐ It is the same battery, so the current remains the same.

7. Item 4

7.1 In the circuit on the right, there is a battery connected to a motor.

What can we say about the measurements on both the Ammeters?

☐ A_1 shows a higher current.
☐ Both Ammeters show the same current.
☐ A_2 shows a higher current.



7.2 **Give a reason for your answer.**

☐ The current is the same in the whole circuit.
☐ Some of the current gets used up in the motor.
☐ All of the current gets used up in the motor.

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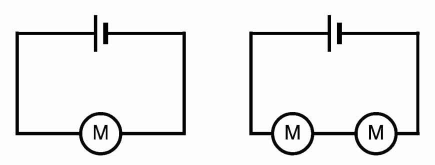
8. Item 6

8.1 A circuit is made from a battery and a motor. The motor is running (shown on the left). Then we add a second motor (shown on the right).

What happens to current in the circuit?



- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller, but not to zero.
- ☐ No current flows.

8.2 **Give a reason for your answer.**

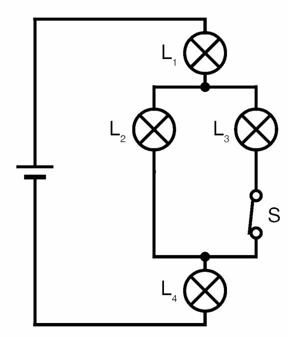
- ☐ The battery is not strong enough to get the current through both motors.
- ☐ It is the same battery, so the current remains the same.
- ☐ The battery cannot push as much current as before through both the motors.
- ☐ Two motors need more current than one.
- ☐ The current is shared over both motors, so it is halved.

9. Item 7

9.1 In the circuit on the right there are four identical light bulbs, connected to a battery. The switch S, as in the picture, is closed to begin with.

What happens to the current through the light bulb L_2, when we open the switch?

- ☐ The current through L_2 gets bigger.
- ☐ The current through L_2 stays the same.
- ☐ The current through L_2 gets smaller.
- ☐ More information is needed to answer this question.



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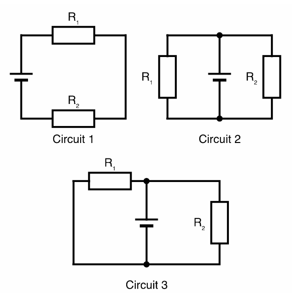
10. Item 9



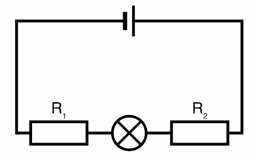
10.1 **In which of the circuits are R_1 and R_2 parallel to each other?**

☐ Circuits 1, 2 and 3 ☐ Circuit 2
☐ Circuit 1 ☐ Circuits 1 and 2
☐ Circuits 2 and 3

10.2 Give a reason for your answer.

☐ For resistors to be parallel their lines (when extended) should not touch.
☐ The same current must go through both resistors.
☐ The resistors must be in different branches of the circuit and have the same voltage over them.
☐ The resistors must be opposite each other in the circuit.

11. Item 10

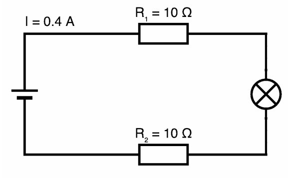


11.1 In this circuit there are two resistors and a light bulb connected to a battery.

What happens to the brightness of the light bulb if R_2 stays the same and we make R_1 smaller?

☐ The light bulb shines brighter.
☐ The light bulb shines no differently.
☐ The light bulb does not shine as brightly.

12. Item 13



12.1 In a circuit with a light bulb and two resistors with resistances R_1 = 10 Ω (Ohms) and R_2 = 10 Ω (Ohms) has a current I = 0.4 A (Amps). The **resistor R_2** is swapped for a resistor with R_3 = 20 Ω (Ohms). **What happens to the current through the light bulb?**

☐ The current is now smaller than 0.4 A (Amps).
☐ The current is the same as before.
☐ The current is now larger than 0.4 A (Amps).

12.2 Give a reason for your answer.

☐ A larger resistor gives more current.
☐ More resistance means the current is lower everywhere.
☐ Current can reach the light bulb from both sides.
☐ The lightbulb takes as much current as it needs.
☐ Some more current gets used up in the light bulb.

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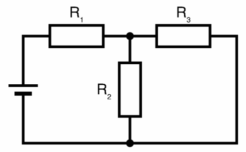
13. Item 14

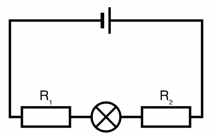
13.1 Which resistors in the picture on the right are in **parallel** to each other?

- ☐ R_1 and R_2.
- ☐ R_1 and R_3.
- ☐ None of the resistors are parallel to another.
- ☐ R_2 and R_3.



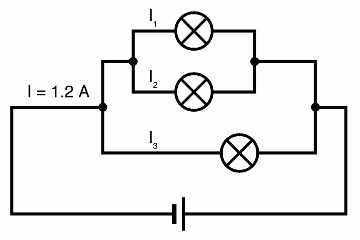
14. Item 15

14.1 In the circuit on the right two resistors and a light bulb are connected to a battery.
If we keep R_1 the same and decrease the resistance of R_2, what happens to the brightness of the light bulb?



- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb does not shine as brightly.

15. Item 16



The light bulbs in the picture are all the same.
The total current is 1.2 A (Amps).
How large are the currents in the branches?
Write the missing currents for I_1, I_2 and I_3.
Example showing how to fill in 12.05 A (Amps):

15.1 Example I =

12.05 A

15.1 Current I_1 = __ __ . __ __ A

15.2 Current I_2 = __ __ . __ __ A

15.3 Current I_3 = __ __ . __ __ A

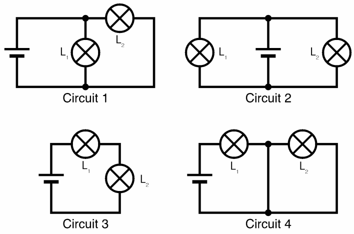
15.4 Give a reason for your answer.

- ☐ All lightbulbs need the same amount of current from the battery.
- ☐ I_3 is the closest so gets the most current.
- ☐ The current splits evenly at each branch in the circuit.
- ☐ As the voltage difference is the same over all the bulbs, so is the current through them.

16. Item 20

16.1 **In which circuits (on the right) are the lightbulbs L_1 and L_2 parallel to the battery?**

- ☐ Circuit 1
- ☐ Circuit 2
- ☐ Circuit 3
- ☐ Circuits 1 and 2
- ☐ Circuits 1, 2 and 4



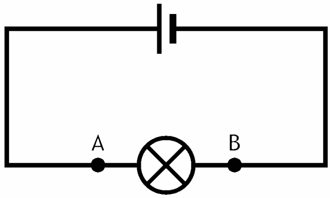
16.2 Give a reason for your answer.

- ☐ For resistors to be parallel their lines (when extended) should not touch.
- ☐ The same current must go through both resistors.
- ☐ The resistors must be in different branches of the circuit and have the same voltage over them.
- ☐ The resistors must be opposite each other in the circuit.

17. Item 22

17.1 The light bulb in the circuit on the right is glowing. **Which of these statements about the currents through A and B is true?**

- ☐ The current is bigger at A than B.
- ☐ The current is bigger at B than A.
- ☐ The current is the same at A and B.

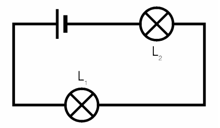


17.2 Give a reason for your answer

- ☐ The current is the same in a series circuit.
- ☐ A and B are the same distance from the battery.
- ☐ Current can get to A and B from both sides of the battery
- ☐ The light bulb uses up some of the current.
- ☐ The light bulb uses up all of the current.

18. Item 21

18.1 Look at the circuit below.
How bright do the light bulbs glow?



- ☐ Both light bulbs glow. L_1 glows brighter than L_2.
- ☐ Both light bulbs glow. L_2 glows brighter than L_1.
- ☐ Both light bulbs glow with the same brightness.
- ☐ L_1 glows. L_2 does not.
- ☐ L_2 glows. L_1 does not.

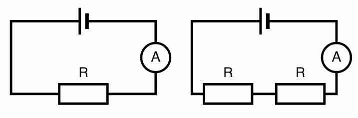
18.2 **Give a reason for your answer.**

- ☐ L_1 uses up all the current. There is no more current left for L_2.
- ☐ L_1 uses up some of the current. So, there is less current left for L_2.
- ☐ The current is the same in the whole circuit.
- ☐ The current is shared between both light bulbs evenly.
- ☐ L_2 is closer to the battery. So, it gets more current.

19. Item 23

19.1 A circuit is built from a battery, a resistor and an Ammeter. The Ammeter shows us the current (picture on the right).
What happens to the current on the Ammeter, when we add a second identical resistance R?

- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller, but not zero.
- ☐ No current flows.

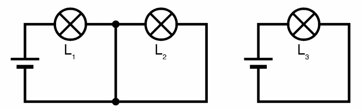


19.2 **Give a reason for your answer.**

- ☐ Two resistors need more current than one.
- ☐ It is the same battery, so the current remains the same.
- ☐ The current is shared over both resistors, so it is halved.
- ☐ The battery cannot push as much current as before through both the resistors.
- ☐ The battery is not strong enough to get the current through both resistors.

20. Item 24

20.1 **Compare the brightness of the light bulbs L_1, L_2 and L_3 in both circuits (see diagram).**



- ☐ Light bulb L_1 glows the brightest.
- ☐ Light bulb L_2 glows the brightest.
- ☐ Light bulb L_3 glows the brightest.
- ☐ Light bulbs L_1 and L_2 glow the brightest.
- ☐ Light bulbs L_1 and L_3 glow the brightest.

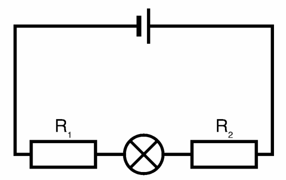
20.2 Give a reason for your answer.

- ☐ L_1 and L_2 power each other.
- ☐ L_1 and L_3 are the same distance away form the battery.
- ☐ L_2 gets more current than the others.
- ☐ L_2 is short circuited and L_1 and L_3 have the same voltage over them.
- ☐ L_3 gets all the current from the battery.
- ☐ The current is shared between L_1 and L_2.

21. Item 25

21.1 In the circuit to the right two resistors and a light bulb are connected to a battery.
If we keep R_1 the same and increase the resistance of R_2, what happens to the brightness of the light bulb?

- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb does not shine as brightly.



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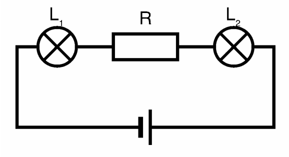
22. Item 26

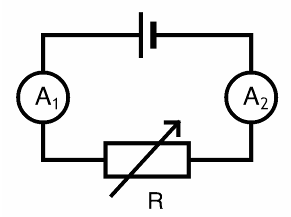
22.1 In the circuit below, both light bulbs L_1 and L_2 glow with the same brightness.
What happens to the brightness of both light bulbs if we increase the resistance R?



- ☐ L_1 stays the same. L_2 gets dimmer.
- ☐ L_1 gets dimmer. L_2 stays the same.
- ☐ L_1 and L_2 both get brighter.
- ☐ L_1 and L_2 both get dimmer.
- ☐ L_1 and L_2 both stay the same.

23. Item 27

The circuit on the right is built from two Ammeters and a variable resistor.
Both Ammeters show us the current.
Now we increase the resistance R.



23.1 **What happens to the current at Ammeter A_1?**
- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller.

23.2 **What happens to the current at Ammeter A_2?**
- ☐ It gets bigger.
- ☐ It stays the same.
- ☐ It gets smaller.

23.3 **Give a reason for your answers.**
- ☐ A larger resistor needs more current than a smaller resistor.
- ☐ It is the same battery, so it gives the same current.
- ☐ A bigger resistance means a smaller current everywhere in the circuit.
- ☐ A bigger resistance means a smaller current after the resistance. So, the current before the resistor does not change.
- ☐ A bigger resistance means a smaller current after the resistance. So, the current before the resistor gets bigger.

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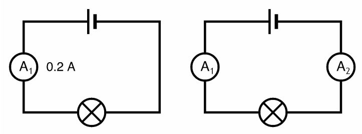
24. Item 28

24.1 In the circuit below the light bulb glows and the Ammeter shows a current of 0.2 A (Amps). Now we put in a second Ammeter A_2 on the other side of the light bulb.
What current does the Ammeter A_2 show?

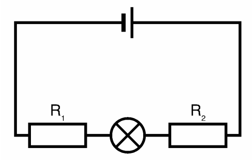


- ☐ More than 0.2 A (Amps).
- ☐ Exactly 0.2 A (Amps).
- ☐ Less than 0.2 A (Amps), but not 0 A (Amps).
- ☐ 0 A (Amps).

24.2 **Give a reason for your answer.**
- ☐ The current is the same in the whole circuit.
- ☐ Some of the current gets used up in the light bulb.
- ☐ All of the current gets used up in the light bulb.

25. Item 29

25.1 In the circuit below two resistors and a light bulb are connected to a battery.
What happens to the brightness of the light bulb if R_2 stays the same and we make R_1 bigger?

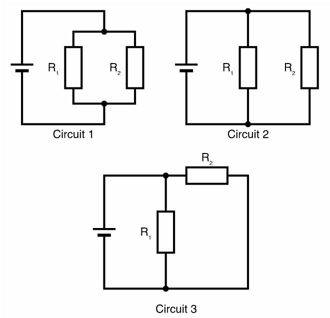


- ☐ The light bulb shines brighter.
- ☐ The light bulb shines no differently.
- ☐ The light bulb does not shine as brightly.

26. Item 30

26.1 **In which of the circuits are R_1 and R_2 parallel to each other?**
- ☐ Circuits 1, 2 and 3
- ☐ Circuit 2
- ☐ Circuit 1
- ☐ Circuits 1 and 2
- ☐ Circuits 2 and 3

26.2 Give a reason for your answer.
- ☐ For resistors to be parallel their lines (when extended) should not touch.
- ☐ The same current must go through both resistors.
- ☐ The resistors must be in different branches of the circuit and have the same voltage over them.
- ☐ The resistors must be opposite each other in the circuit.



27. Item 31

Fill out the following two questions like in the example. The example below shows how you would fill in 4.25 V as an answer:

27.1 Example:

4.25 V

Look at the following circuit.
How high is the voltage (potential difference):

27.1 Between points 1 and 2:

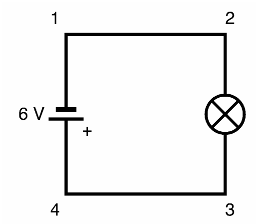
. V

27.2 Between points 2 and 3:

. V

27.3 Between points 3 and 4:

. V



We now put another of the same light bulbs between point 3 and 4.
How high is the voltage in the circuit with two light bulbs:

27.4 Between points 1 and 2:

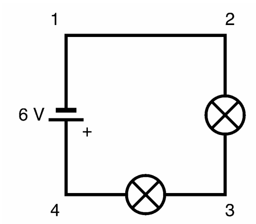
. V

27.5 Between points 2 and 3:

. V

27.6 Between points 3 and 4:

. V



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28. Item 32

The following circuit is made from two identical light bulbs and a closed switch.
How high is the voltage (potential difference):

28.1 Between points 1 and 2:

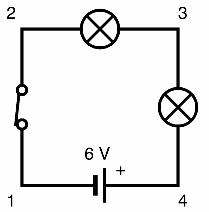
☐☐.☐☐ V

28.2 Between points 2 and 3:

☐☐.☐☐ V

28.3 Between points 3 and 4:

☐☐.☐☐ V



Now we open the switch between points 1 and 2.
How high is the voltage (potential difference):

28.4 Between points 1 and 2:

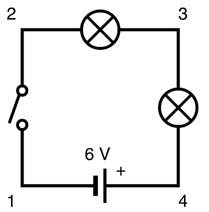
☐☐.☐☐ V

28.5 Between points 2 and 3:

☐☐.☐☐ V

28.6 Between points 3 and 4:

☐☐.☐☐ V



A.3 Table Showing Codes in New and Redeveloped Tests

	Case 1	Case 2	Case 3	Case 4
Current Use	I21: A1B2 or A2B5	I4: A1B2 or A3B2	I28: A3B2 or A1B2	I22: A1B2 or A2B2
A Battery is a Constant Current Source	I3: A3B4	I27: A2B2C2	I23: A2B2	I6: A2B2
Current is Independent of Resistance	I25: B2 and I29: B2	I10: A2 and I15: A2	I10: A2 and I25: B2	I15: A2 and I29: B2
Inverse Resistance	I3: A1B3	I23: A1B1	I6: A1B4	
The Higher the Resistance, the Higher the Current	I3: A2B3	I6: A3B4	I23: A3B1	
Local Argumentation (Looking at Individual Points on the Circuit)	I16: $I_{1,2} = 0.3A$, $I_3 = 0.6A$	I7: A2	I24: A3	Redundant I16: B3
Sequential Argumentation (Going Through Components Step-by-Step)	(I10: A2 and I29: B2 and I15: A1 and I25: B3) or (I10: A1 and I29: B3 and I15: A2 and I25: B2)	(I2: A1 and I13: A2) or (I2: A2 and I13: A1)	I27: A2B3C4	I26: A1,2
General Problems Recognising Parallel Circuits	I9: A2,3,4	I20: A2	I14: A1,2,3,5	I30: A2,3,4
Parallel Opposite Confusion	I9: A4B1	I20: B1	I30: A4B1	
Geometrically Parallel Confusion	I9: A1,2B4	I20: A2B4	I30: A1,4B4	
Resistors give Current	I2: A3B1	I13: A3B1	I24: A4B1	
Current Impelled by Resistances	I2: A2B4	I13: A2B4	I16: $I_{1,2,3} = 0.4A$ and B1	
Current and Proximity	I16: $I_3 > I_{1,2}$ and B2	I22: A3B2	I24: A5B3	

Table A.1: Table Showing Alternative Conceptions in Answer Combinations. Below the vertical line midline marker are new answer combinations developed on the basis of chapter 3.

B Vocabulary List

B.1 List of Possibly Unknown Words used in "An Introduction to Electric Circuits"

List of words rarer than rank 16,577 appearing in "An Introduction to Electric Circuits" and an explanation as to whether they are contained within the vocabulary list - this list can be seen in the booklet for EG2.

	Included in Vocab list.	Root Word(s)	Root Word Freq.	Notes
airflow	Yes	air, flow	376, 2019	Literal compound of two common words.
ammeter	Yes	-	-	Topic specific vocabulary.
ampere	Yes	-	-	
appliance	Yes	-	-	In the phrasal word "household appliance".
attaches	No	attach	9565	Inflection of common verb.
behaves	No	behave	6649	Inflection of common verb.
bumping	No	bump	7670	Inflection of common verb.
conditioners	Yes, as air conditioner	-	-	In the phrasal word "air conditioners"
conduction	Yes	-	-	Topic specific vocabulary.
conductive	Yes	-	-	
conductors	Yes	-	-	

cores	Yes, as atomic core	core	1835	Plural of common word, used here in an unfamiliar context.
deriving	Yes	derive	12866	Topic specific vocabulary, only used in extension questions.
diagrams	Yes	diagram	10208	Plural of technical word.
dimmer	Yes	-	-	In the phrasal word "dimmer switch".
electrocuted	Yes	electrocute	74750	Uncommon root word.
filament	Yes	-	-	Topic specific vocabulary.
fizzy	No	-	-	Common British English word. Corpora predominantly American English. Compare with “soda” with rank 7283.
flowed	No	flow	2019	Inflection of common verb.
footballs	No	football	910	Inflection of common noun.
formulae	Yes	formula	3103	Irregular inflection of technical noun.
glows	No	glow	9202	Inflection of common verb.
hairdryer	No	-	-	Common household object.
halogen	Yes, as halogen bulb.	-	-	Topic specific vocabulary.
halved	No	half	372	Inflection of common verb.
hob	No	-	-	Common British English word. Corpora predominantly American English. Compare with “stove” with rank 11435.
insulating	Yes	-	-	Topic specific vocabulary.
insulator	Yes	-	-	
insulators	Yes	-	-	
interfered	No	interfere	7953	Inflection of common verb.
interferes	No	interfere	7953	
lowers	No	lower	780	Inflection of common verb.
mains	Yes, as mains voltage.	main	533	Plural of common word, used here in an unfamiliar context.

mathematically	Yes	mathematics	5620	Common word, used here in an unfamiliar context.
millimetre	Yes	-	-	Topic specific vocabulary.
mover	No	move	487	Inflection of common verb.
movers	No	move	487	
narrower	No	narrow	3689	Inflection of common adjective.
ohm	Yes	-	-	Topic specific vocabulary.
ohmic	Yes	-	-	
pedals	No	pedal	11906	Inflection of common noun.
physicists	Yes	physicist	15331	Topic specific vocabulary.
plugged	Yes	plug	6220	Topic specific vocabulary.
plugs	Yes	plug	6220	
pressurised	No	pressure	1036	Inflection of common noun.
puncture	Yes	-	-	Uncommon noun.
pylons	Yes	pylon	36791	Uncommon noun.
raisin	No	-	-	Although uncommon in written English, a common lunch item for children.
recognising	No	recognise	7630	Inflection of common verb.
resistances	Yes	-	-	Topic specific vocabulary.
resistor	Yes	-	-	
resistors	Yes	-	-	
rhys	No	-	-	Name
settles	No	settle	4032	Inflection of common verb.
slowest	No	slow	1511	Inflection of common adjective.
slows	No	slow	1511	
sockets	Yes	socket	14769	Topic specific vocabulary.
spaced	No	space	599	Inflection of common verb.
squashed	No	squash	13905	Inflection of common verb.
straws	No	straw	8008	Inflection of common noun.
swapped	No	swap	8872	Inflection of common verb.
swapping	No	swap	8872	
toaster	No	-	-	Common household appliance.
torches	No	torch	10158	Inflection of common noun.

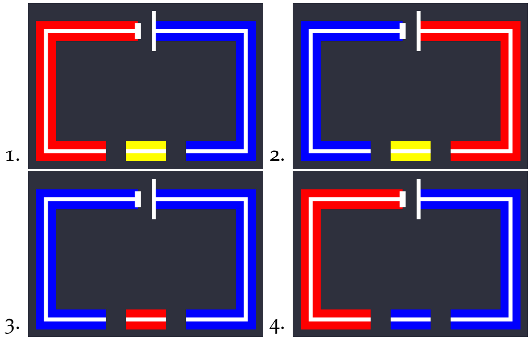
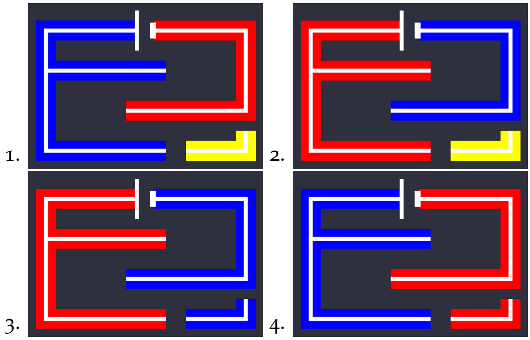
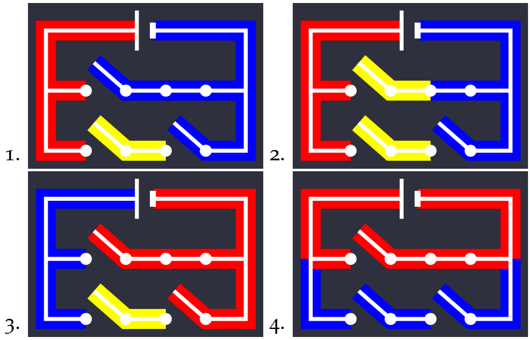
triples	No	triple	4695	Inflection of common verb.
tripling	No	triple	4695	
unopened	No	open	317	Compound of common adjective.
vibrate	Yes	-	-	Topic specific vocabulary.
visualisation	Yes	-	-	Topic specific vocabulary.
volt	Yes	-	-	Topic specific vocabulary.
voltmeter	Yes	-	-	
voltmeters	Yes	-	-	
volts	Yes	-	-	

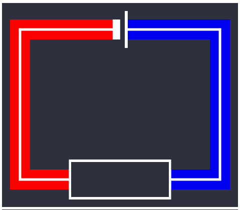
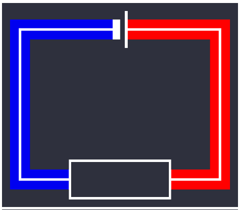
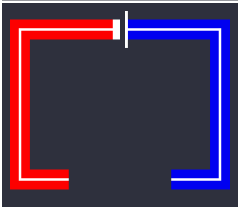
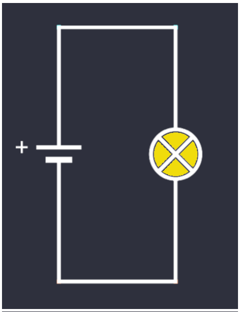
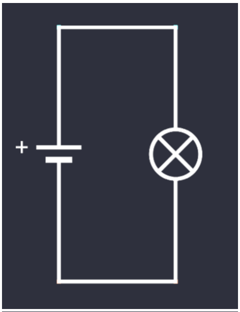
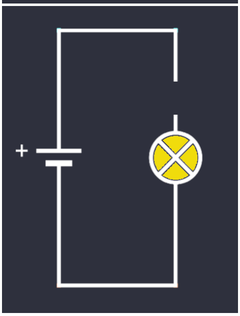
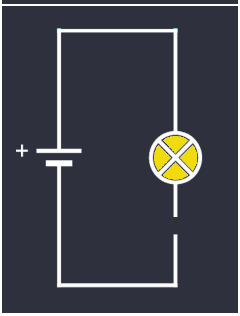
Table B.1: List of Possibly Unknown Words used in "An Introduction to Electric Circuits"

C Questions Featured in "Talking Circuits"

C.1 Table Showing Questions in Each Tablet Lesson

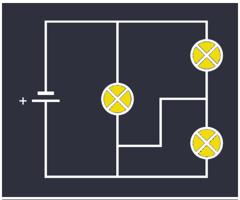
Question	Answer Options
Lesson Three	
Describe what a battery in an electric circuit does. Choose the correct statement.	1. The battery gives current to the bulb to use up all of. 2. The battery gives current to the bulb to use up some of. 3. The battery gives energy to the bulb, carried by the current. 4. The battery charges the bulb up.
Explain what happens in the circuit to make the light bulb glow.	1. Chemical energy from the battery is transferred to electrical energy. This is transferred to heat and light energy in the bulb. 2. The battery provides energy to get used up in the bulb. 3. The battery makes electricity that gets used up in the bulb. 4. Light and heat energy is transferred from the battery to the bulb.
Why do we need two wires for the light bulb to glow?	1. Only with two wires does enough current (electricity) get to the bulb. 2. Two wires let current (electricity) flow to the bulb and then back. 3. Two wires let energy flow to the bulb and then back. 4. We need both positive and negative current (electricity).

Lesson Six	
How would you colour code this open circuit?	
How would you colour code this open circuit?	
How would you colour code this open circuit?	
What does a closed switch act like?	1. A gap in the circuit 2. A resistor 3. A piece of wire 4. An electric pressure

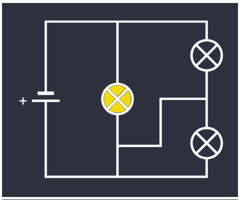
What does an open switch act like?	1. A gap in the circuit 2. A resistor 3. A piece of wire 4. An electric pressure
How would you colour code this closed circuit?	1.  2.  3.  4. 
Lesson Eight	
Which of the diagrams shows the Light Bulbs lit up correctly?	1.  2.  3.  4. 

Which of the diagrams shows the Light Bulbs lit up correctly?

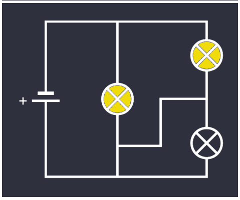
1.



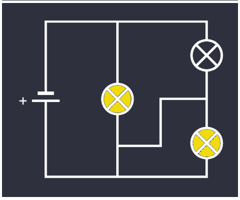
2.



3.

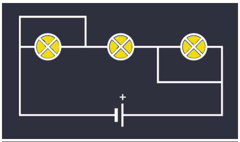


4.

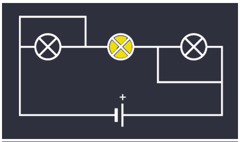


Which of the diagrams shows the Light Bulbs lit up correctly?

1.



2.



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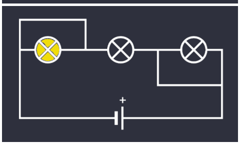

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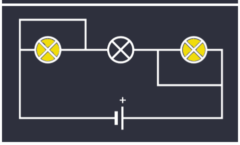
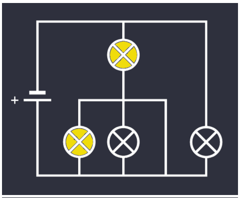
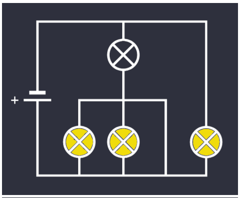


Which of the diagrams shows the Light Bulbs lit up correctly?

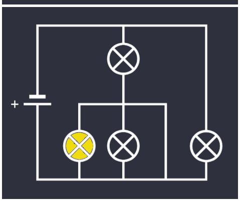
1.



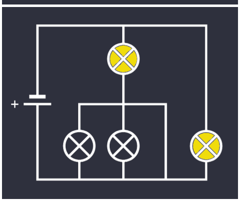
2.



3.



4.



Which diagram shows the correct currents?

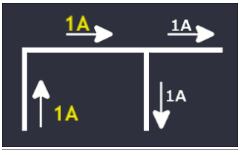
1. 

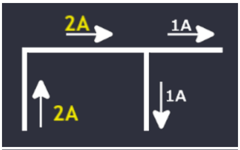
2. 

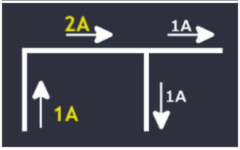
3. 

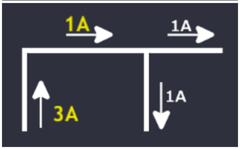
4. 

Which diagram shows the correct currents?

1. 

2. 

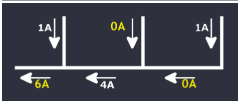
3. 

4. 

Which diagram shows the correct currents?

1. 

2. 

3. 

4. 

Lesson Ten

Rob thinks that the current measured by the ammeter with a "?" is less than 6 A. He thinks that more resistors use up more current. What actually happens to the current?

1. More resistors do use more current.
2. More resistors make more current.
3. Regardless of how many resistors there are, the battery always gives the same current.
4. The current does get lower, but it's not used up.

Rob thinks that the current measured by the ammeter with a "?" is less than 6 A. He thinks that more resistors use up more current. How would you explain where he's got confused?	1. More resistors make more current, but only after the Ammeter. 2. Current works like a bike chain, it pushes energy around the circuit but does not get used up. 3. Even though there are more resistors, they come after the ammeter so nothing changes. 4. The battery provides as much current as it can, so it is always the same.
What does the "?" Ammeter show? More or less than 6 A?	1. More than 6 A. 2. The same, 6 A. 3. Less than 6 A. 4. We need more information about the battery.
What does the "?" Ammeter show? Without using V=IR. Write a number.	[Numerical Input]
Which explanation best fits how you got your last answer.	1. 6Ω means the Current is 6 Amps. There are 12Ω in the second circuit, which means the Ammeter shows 12A. 2. The Resistance has doubled so the Current has doubled to 12A. 3. The Resistance has doubled so the Current has halved to 3A. 4. The battery is giving 6A.
Lesson Twelve	
Choose the false statement about Potential Difference: Write the true statements in your booklet.	1. Is a difference in potential between two places in the circuit. 2. It can only exist if a Current is flowing. 3. Causes a Current to flow. 4. Is measured by a Voltmeter in Volts.
Choose the false statement about Current: Write the true statements in your booklet.	1. Current is the amount of charge per second flowing around the circuit. 2. Current is measured by an Ammeter in Amps. 3. The amount of current flowing into a junction is the same as current that flows out. 4. Current gets used up in the light bulbs as it goes through.

Choose the false statement about Resistance: Write the true statements in your booklet.	1. Resistance tell us how much a material interferes with the flow of electrons. 2. The higher the resistance, the lower the current. 3. The higher the resistance, the higher the current. 4. The Resistance of a component can be calculated by the Potential Difference over it, divided by the current through it.
Choose the correct statement about a series circuit.	1. Electric potential drops bit by bit over the light bulbs in series. 2. Electric potential is the same everywhere in a series circuit. 3. Electric potential gets used up in a series circuit. 4. The light bulbs make the electric pressure in a series circuit.
Choose the correct statement about a series circuit.	1. Electric Potential is the same in the whole circuit. 2. Electric Potential drops more over the resistance closer to the battery. 3. Electric Potential drops the same over the same resistance. 4. Electric Potential always drops by the same amount over a resistor.
Choose the correct statement about a series circuit.	1. Electric Potential is the same in the whole circuit. 2. Electric Potential drops more over higher resistances. 3. Electric Potential drops less over higher resistances. 4. Electric Potential always drops by the same amount over a resistor.
Choose the correct statement about a series circuit.	1. Each light bulb uses a bit of the potential up. 2. The sum of the potential difference over all of the resistors is always the potential difference from the battery. 3. The potential difference is lost to the atmosphere. 4. The battery changes the potential difference it gives depending on the resistances.

D Additional Figures and Tables

D.1 Inter-item Correlations

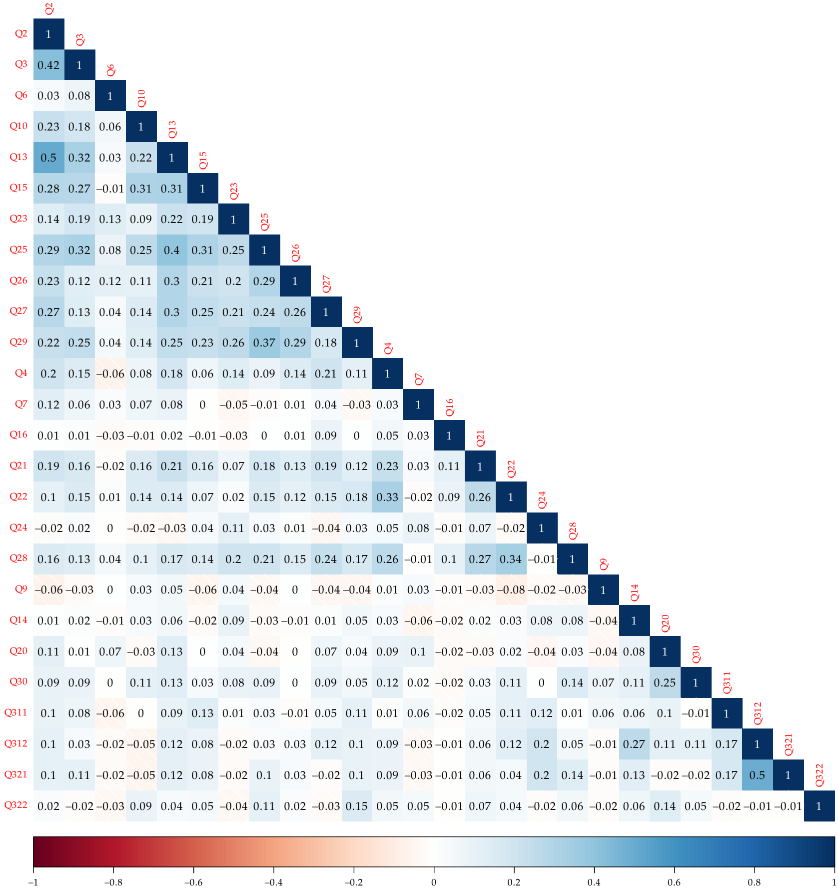


Figure D.1: Inter-item Correlation of each Item for the new Rubric

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Learning about electric circuits demands abstract thinking, new vocabulary and using concepts that contrast with learners' prior knowledge. Drawing on helpful ideas from everyday experiences with pressure, such as bike tyres and balloons, and evidence from cognitive science, I present an accessible approach using the electron gas model for the first time in English.

Building on the design principles of digital tools and collaborative learning, I designed a tablet-based system to scaffold small-group talk to foster conceptual change: "Talking Circuits". This prompting tool enabled real-time assessment of student-student talk, so that lengthy and expensive collaborative learning interventions could be more easily implemented. In a comparative study of 228 learners, aged 12 to 14, I compared two conditions taught using the electron gas model: one using standard classroom materials and the second adding the "Talking Circuits" application. Concept knowledge and motivation were measured in pre- and post-tests.

Results show no significant changes in learning outcomes. The only statistically significant, albeit small, changes were reductions in perceived competence. This tentatively points to the need for longer implementation timeframes and teacher professional development. Learning electricity is demanding; conceptual change likely needs more time than typical British timetables allow.

Logos Verlag Berlin

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