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Investigating Student Approaches to Rearranging Circuit Diagrams

Leah M. Ridgway and Tom Cox

Abstract— **Contribution: This study uses a qualitative research method to analyze interviews where participants simplified an electric circuit while explaining their thought process. Background: Rearranging circuit diagrams is a fundamental skill in electrical and electronic engineering, yet students can struggle with unfamiliar configurations. Current research in the discipline is often quantitative, centered on conceptual understanding. By using a qualitative method, the process of 'how' students interact with circuit diagrams is investigated. Research Question: How do students approach circuit diagram simplifications? Methodology: 15-minute individual discussions with 10 participants (undergraduate Years 1–4) simplifying an unconventionally-presented circuit diagram were recorded. Reflexive thematic analysis was used to identify common themes. Findings: 1. Participants initially rely upon pattern recognition to solve circuit problems before applying other analysis techniques. 2. Two rearrangement methods were identified: 'component focused', where combinations of components are grouped and then connected together, and 'ground focused' where components in the circuit are related to ground and then connected together. 3. Students using a ground focused strategy were less hesitant in their circuit rearrangement process. 4. Students broadly used mechanicalistic methods of error checking, selecting software tools rather than applying conceptual understanding.**

Index Terms— **Circuit diagrams, Engineering education, Qualitative methods, Student learning, Thematic analysis**

I. INTRODUCTION

THE manipulation of circuit diagrams is a fundamental skill used by electrical/electronic engineers to model, simplify and understand systems.

To succeed in their studies, students need to work with circuit diagrams of increasing complexity, culminating in the ability to work with unfamiliar designs and the creation of their own. The professional training provided by engineering courses requires students to become adaptive, able to apply existing understanding to new problems, as stated for degree accreditation. Adaptability is a graduate disposition sought after by industry [1].

Rearranging circuit diagrams is a disciplinary skill that all students are expected to demonstrate and is framed within this paper as a first step in developing and demonstrating adaptive expertise. By understanding the processes in which students engage when resolving simple, previously unseen circuit problems, educators can develop the tools to support flexible application of learning, rather than repetition of rote-learned problems.

The analysis uses a qualitative method: reflexive thematic analysis (RTA), which puts students' own words as the focus of the research. Results are presented as a narrative where observations and quotes from participants are used to illuminate features and are interwoven with existing literature on these concepts. This allows investigation of broad themes in student perception to draw educationally relevant conclusions and outcomes.

II. THEORETICAL ASPECTS

Adaptive expertise is a theory of learning where prior knowledge can be applied and adapted to novel settings. This and its counterpart 'routine expertise' were identified by Hatano and Inagaki [2]. Routine experts work efficiently on previously seen problems, whereas adaptive experts can apply existing knowledge to unfamiliar situations.

While routine expertise is valuable in certain areas, to meet the Washington Accord benchmark competencies for accredited engineering degrees, students need to demonstrate adaptive expertise. At Bachelor's level, student learning outcomes must demonstrate the ability to work with "broadly defined" problems, which the IET in the UK elaborates upon as problems solvable "by the application of … well-proven analysis techniques" [3]. For higher level degrees this requirement increases to working with "ill-defined" or "complex" problems [4], [5].

Several methods to develop adaptive experts have been proposed which discuss the optimal difficulty or challenge of task required [6], [7]. Within engineering, McKenna [8] observed that curriculum structures can result in students being unable to take tools from one setting and apply these to a new context. The computational adaptive expertise (CADEX) framework [9] recognizes that much time within engineering curricula is spent developing analytical and computational knowledge, and it considers an approach for assessing how students apply this prior learning to design solutions.

The work in this paper interrogates the process by which students attempt to demonstrate adaptability in simplifying an unconventional circuit problem, rather than considering the end product such as in assessment performance. By understanding

This work was supported by the Department of Electrical & Electronic Engineering, University of Nottingham, UK.

This research involved human participants and was approved by the Faculty of Engineering Ethics Committee at the University of Nottingham, UK under Application 2022-86 and performed in line with university requirements.

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how students approach an unfamiliar simple circuit, insights can be drawn on how academics should approach their teaching practice to foster flexibility from an early stage in degree programs.

Within electronic engineering specifically, research on how students interact with circuit diagrams is limited. A qualitative study [10] that focused on students' understanding of real-world electrical phenomena to illuminate the deployed models, concluding that these are influenced by disciplinary tools such as circuit diagrams. Turner [11] focused on teaching analysis tools within a case study structure, considering student performance before and after a curriculum change. This found that students were often inconsistent in their logic when approaching problems. Herman, Loui, and Zilles [12] investigated student misconceptions in solving digital circuit problems, noting that "subjects relied heavily on the physical arrangement of circuit components" to manage the cognitive load of larger circuits. A study investigating student conceptual understanding of operational amplifiers highlighted that participants struggled to apply basic circuit rules (Ohm's law, Kirchoff's rules) to these more complex circuits [13].

Literature on student misconceptions in fundamental concepts such as voltage and current is more extensive, as this draws also on research within physics education. As a result of this disciplinary lens, there is a focus on concepts rather than applications; simple circuits diagrams are often used within the question framing, however, the manipulation of diagrams is not within the scope of that work [14], [15], [16], [17], [18]. Where diagrams are analyzed within a study, the analysis is upon the answer produced and less so on the process employed by the student that resulted in that answer [19].

II. RESEARCH PURPOSE

The authors observed in the course of their own work that students are generally confident in producing a solution to a familiar problem, but less confident in applying fundamental circuit analysis tools to novel situations or to unconventionally drawn schematics. This study attempts to understand better how undergraduate students approach these problem types by speaking directly with students while they rearrange a previously unseen circuit diagram.

Currently there is little literature on how students in electronic engineering conceptualize diagrammatic problems and approach their solutions. This study was designed to understand the processes used by students in rearranging a simple yet unfamiliar circuit as the first step in demonstrating adaptability within the discipline. The adaptability under investigation is in relation to applying knowledge of circuit theory to an unseen problem, rather than transferring understanding to a different context such as in a capstone project.

This work uses a qualitative analysis framework to focus on student processes in solving a circuit problem, rather than limiting discussion to the final product. This method has been used to understand student learning within engineering education, physics and chemistry [10], [20], [21], [22]. RTA was selected to address the 'how' and 'why' of student learning in the discipline, taking the frame that students are active partners in their education. This work also suggests areas for future investigation to understand student flexibility in applying disciplinary fundamentals.

III. METHODS

The research process and analysis method is detailed in Fig. 1 and elaborated upon within this section.

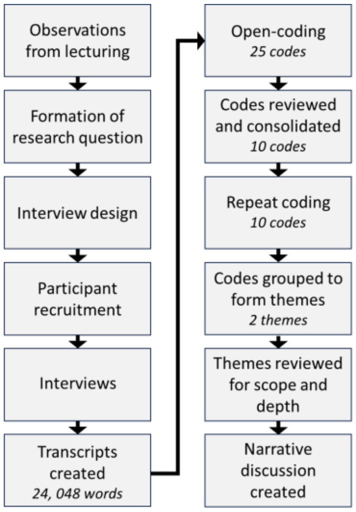

Fig. 1. Research design, data collection and analysis method.

A. Reflexive Thematic Analysis

RTA was employed to explore the data, based upon the Braun and Clarke method [23], which specifically acknowledges the integral role of the researcher within the research process – a parallel to the integral role of the lecturer in influencing the learning process of students. RTA arose within psychology [24] as a method of "developing, analyzing and interpreting patterns across a qualitative dataset" [25]. While the content of engineering and science is quantitatively focused, the process of learning is suited to a qualitative analysis as this is an individual and subjective experience. Thematic analysis was selected as it inherently provides flexibility; the researchers wished to explore what the participants would bring up in discussions themselves rather than testing a hypothesis or evaluating an intervention.

As part of acknowledging the role of the authors' interaction with the participants in the research process, this work is weighted towards the following theoretical assumptions [26]:

Constructivist epistemology: Repeated themes are important in understanding students' approaches and the confidence with which these are presented. If multiple participants raise the same areas, these are weighted as more prominent in the narrative. The relative confidence of the participant is also important in the investigation of solving processes. Pauses are recorded in the transcript as an indication of hesitation;

Experiential data orientation: The words of participants were taken as a reflection of their thoughts without considering

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any implicit meaning that may be present. What participants are willing to share within the discussions to staff is likely to be reflective of dialogue around circuit problems in other educational contexts;

Inductive data analysis: Coding was driven from the transcripts of interviews, rather than applying a pre-determined set of codes to responses. The RTA method was selected as appropriate to be explorative of what students would discuss, so a pre-decided codebook was not applied to the data;

Semantic data coding: The codes produced are descriptive of the areas brought up in discussion by participants, as this is more representative of a teaching environment than would be a latent data coding approach where researchers would 'read between the lines' for meaning.

B. Participants – Demographics and Recruitment

Undergraduate students in Years 1–4 within the Department of Electrical & Electronic Engineering at the University of Nottingham, UK, were invited via email to participate in an individual discussion session in Spring 2023. Recruitment emails included the incentive that participants could opt to be entered into a prize draw for an Amazon voucher. Informed consent was obtained. Participation was voluntary; students were reminded contributions were not linked to their studies; and that that they could withdraw at any time. Additionally, their approach was the focus of the research, not their solution. Ten students participated in the study (six in-person, four online), with representation from all year groups. Further demographic data was not captured, in order to enhance the anonymity of participants. All participant information forms were available in advance of students deciding to participate.

C. Interview Design

Each interview lasted for 15 minutes and was audio recorded. All students were given the same instructions *"I'm going to show you a circuit diagram and I'd like you to talk me through your working as you rearrange it. Your answer isn't important, it's your process that is. The circuit shown has three points labelled A, B and C. Point A is the same connection on both parts of the circuit. Talk me through your working as you rearrange this circuit into a single diagram with a single ground line."* The circuit diagram is shown in Fig. 2 and was purposefully kept to a minimal set of components to reduce cognitive load on participants so that the focus would be on the rearrangement process.

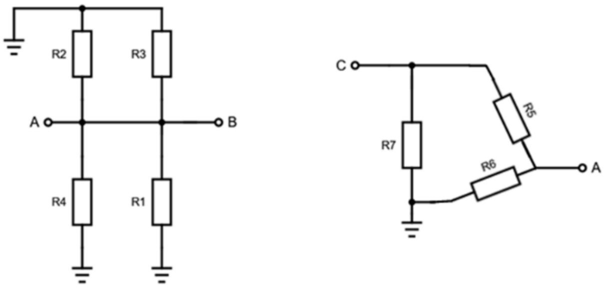

Fig. 2. Circuit diagram problem used in the research.

The format was purposefully kept unstructured to encourage students to discuss their methods, with prompting questions such as "can you elaborate on your approach here?". Feedback was not given on solutions, nor were misconceptions about circuit properties highlighted during the interviews, as the researchers wished to record an authentic account of students' understanding. Once students had arrived at their final answer, they were asked to discuss:

- how they error check work;
- their preference for resistors indicated with labels or with component values.

Participant drawings were retained and incorporated into the analysis.

D. Data Analysis Method

Transcripts were produced from the audio recordings, including capturing the length of pauses and when participants displayed considerable confusion, confidence or satisfaction during the conversation. Transcripts incorporated notes on which part of the diagram the student was drawing at a particular point in order to link thought processes to sketches.

The first analysis stage was a line-by-line (open coding) method where each transcript was coded to identify the area of discussion brought up by the participants (inductive coding). Examples included "joining circuits together"; "doing, without thinking"; and "recognizing the common ground".

Codes were then reviewed, with similar areas grouped together to create ten top-level codes (Fig. 3). The transcripts were then re-analyzed and coded with the new code book to allow different student inputs in the same areas to be compared.

The top-level codes were grouped into two themes, and reviewed to ensure they were of appropriate scope and depth to allow a meaningful narrative to be written.

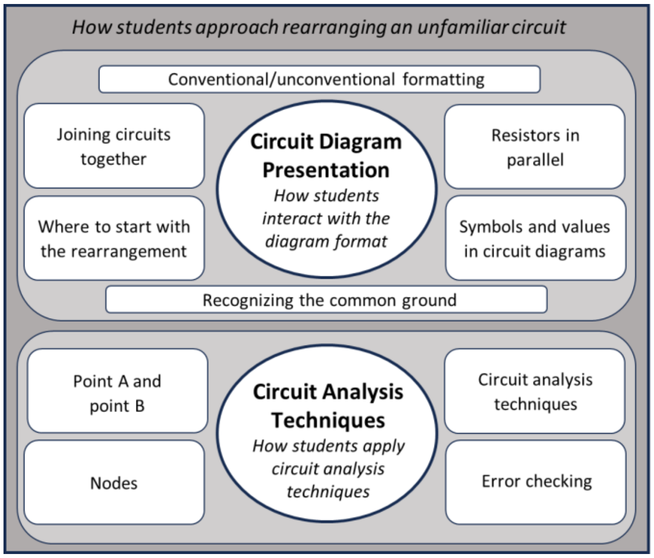

Fig. 3. The codes grouped into themes (thematic map) in this work on how participants solve an unseen problem.

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IV. NARRATIVE DISCUSSION

A. Circuit Diagram Presentation: How Students Interact with the Diagram Format

This theme discusses how students complete an initial analysis of a circuit.

Where to Start with the Rearrangement

The majority of participants initially inspected the diagram for familiar layouts before further analysis. The circuit on the left was the most common starting point because it is in a more familiar layout. For example:

Intuitively this [indicating left circuit] is easier than this [indicating right circuit] and that's because this [left circuit] is similar to many problems I've seen before.

The limitation of using pattern recognition as an initial method was demonstrated when most students did not acknowledge the ground line at the top left of Fig. 2 until later in their working, or when students mistook a resistor combination for a potential divider. One participant stated that pattern recognition was an effective study technique: *"if there's an example, yeah, or something that you see in a past paper, just learning that is most efficient"*. Other researchers have observed that when curricula focus on specific circuit configurations, this results in students being able to answer similar questions correctly, but are less able to adapt to different presentations [27], demonstrating the challenge of building flexible analysis into the curriculum. One participant explicitly acknowledged the limitations of familiarity as an analysis technique: "*These look like potential dividers [R1-R4], so you could sort of, you might get tricked into thinking that they're not all in parallel".*

The other reason for starting on the left was because this was the "first" part of the diagram. This perception of the starting point is most likely due to the majority of participants being from cultures who read left-to-right. Within neuroscience, reading direction has been linked to directionality bias within visuospatial functioning [28], therefore, within a global education sector it would be of interest to understand the potential impact on teaching and learning from the lexical backgrounds of both faculty (those setting the questions) and students (those solving the questions).

The final approach to simplifying the circuit was joining the circuit together at point A into a single diagram (used by a minority of students).

Redrawing the Circuit

When interacting with the diagram, participants operated either a "component focused" or "ground focused" strategy to produce their simplification.

Conventional/Unconventional Formatting

Fig. 4 demonstrates the most prevalently used component focused strategy, where a visual inspection was used to initially group R2 and R3 in parallel, and R4 and R1 in parallel followed by then deciding the connection between these pairs of resistors (indicated by the multiple annotations on the diagram). When deciding how resistors were connected using this method, the visual layout of the components in relation to each other was the focus of the process. This led to details such as the ground connections for R2 and R3 being missed during the initial solution. This error was sometimes not corrected, or was identified later on only after a more detailed inspection, or when participants reviewed their work (all participants were asked if they had reached their final rearrangement during the interview). Students would be unlikely to receive this external prompting to consider their answer in many learning situations, so it is important to acknowledge the presence of the researcher in this context.

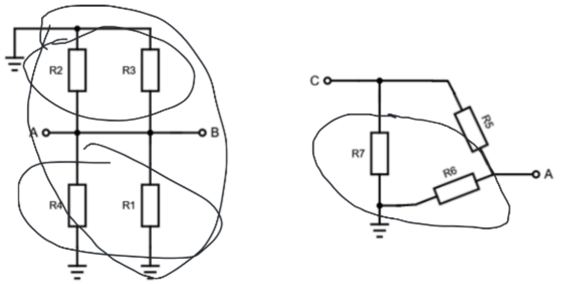

Fig. 4. Example of a component focused method.

Recognizing the Common Ground

In a ground focused strategy, a ground rail was drawn onto a diagram first and components were then connected from this to construct an answer. In Fig. 5, the participant started by connecting the ground terminals of R4 and R1 then extending this to the left, adding R6 and then connecting up to point A with the other terminal. The common ground connection was expanded to R7, then the connection from R7 to point C, and finally the connection between C and A was included with resistor R5.

Participants who employed a ground focused approach, considering the connections of components over the placement of components in the diagram were observed to be less hesitant in their rearrangement process.

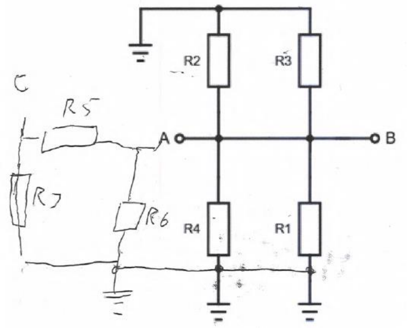

Fig. 5. Example of a ground focused method.

In the later part of their method, participants viewed reducing the number of ground terminals indicated on the diagram as important in simplifying the circuit, interpreting "with a single ground line" as a single ground rail used to join circuit elements, rather than using the convention seen in some textbooks as shown on the right-hand side of Fig. 6. The inclusion of a rail connecting the grounds together was perceived to make the diagram look like a *"completely different"* circuit.

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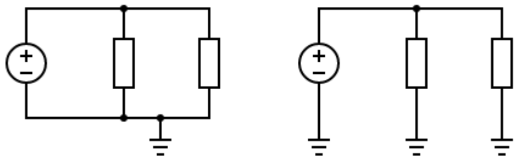

Fig. 6. Examples of different accepted conventions for drawing ground connections.

The reason for this is potentially due to students views of a single ground plane construction in practical circuits, in comparison to the various equivalent notations that are equally valid. An alternative reason is familiarity with the presentation of circuits in notes and textbooks and prior learning of circuits. In pre-university study, electricity is often introduced in a ‘current-first’ model where voltage is introduced much later in a curriculum, resulting in students using current (rather than voltage) as their fundamental tool for analyzing electric circuits [29]. If current is viewed as the primary analysis tool for understanding circuit behavior, adding a line to join the grounds together would make the flow of current easier to perceive. Whereas if voltage is the primary analysis tool, the visual connection of ground lines is less important. It is possible that the current-first model needs to be addressed at university level to support students progressing in their analysis skills.

Dealing with Diagonals

When simplifying the circuit on the right of Fig. 2, all participants removed the diagonal connections and replaced them with perpendicular components. There was a split between rearranging and then connecting the circuits, or adding components R5-R7 directly onto their existing simplified circuit. The reasons for this were explained as either a preference using more emotive language, or as a way to better understand a problem:

> *I think when it's like a straight square format or diagram, it's much more easier to comprehend. Whereas when they're bent and stuff it makes it kinda complicated in my mind. It's something psychological!*

Resistors in Parallel

All students quickly identified that R1 and R4 are in parallel, as are R2 and R3. Time to progress from this point varied as connections were considered in more detail after first impressions and where participants started to make errors:

> *It's a bit fiddly though with the ground on either side.... So now looking at it further uhh ... I can see that R4 and R1 aren't actually in parallel - although they're side by side they're not actually connected full parallel.*

This result where students find unconventional presentations of parallel components confusing is supported by Widodo, Rosdiana, Fauziah and Suryanti, [19]; when asking 30 trainee science teachers to connect three resistor symbols presented on a horizontal line in parallel, the author noted “the standard drawing of parallel circuits in the [text] book seems to make students not recognize the essence of parallel circuits”.

Variation in Presentation of Final Circuit

What participants viewed as their final simplification of the circuit varied, demonstrated by eight of the ten participants with electrically equivalent circuits in Fig. 7. Each conformed to disciplinary conventions (perpendicular components, agreed component symbols). All have individual presentational variations, but the most frequent presentation showed separate resistors as presented in the initial problem. The differences highlight how flexibility is vital in applying understanding, as multiple correct methods of schematic presentation were produced by participants from the same educational program. The wide-ranging visual disparity of developed solutions from an identical initial circuit further highlights the challenges of, and requirement for, the development of adaptive expertise in the domain.

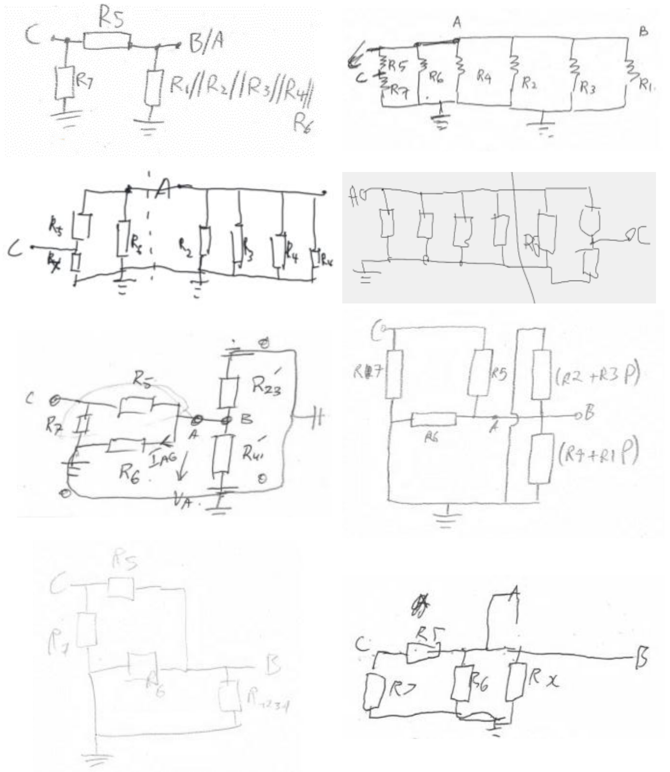

Fig. 7. Participants' final circuit sketches that are all electrically equivalent.

Symbols and Values in Circuit Diagrams

After completing their simplification, participants were asked if it would have been easier, harder or no different to rearrange, if the resistors had values (such as 10 kΩ) rather than labels (such as R1):

- two participants preferred labels, explaining that it protected them from making calculation mistakes at the start that would propagate through a solution;
- a further two said there was no difference, but qualified that values would be more convenient for finding equivalent resistances;
- the majority had a strong preference for component values due to making calculations easier.

I work better with mesh and nodal analysis if I actually have numbers, so if I know the current and that kind of thing I can do it much quicker, because in my head I can do the maths for each thing quickly, and for me it's then quicker if I can have the numbers, but if I don't, generally I say R1 and R2, it just isn't as quick and it's not as intuitive.

Within this study, the preference for numerical values did not limit the ability of participants to simplify the circuit diagram. However, the mechanicalistic application of algorithms and equations can be used by students to conceal or compensate for weaknesses in understanding of fundamental qualitative concepts [15], [30]. The preference may also be due to the relative familiarity of numerical problems from tools for teaching and assessment within the discipline, which have become more widely adopted as a method to provide both individualized feedback and efficient assessment with large class sizes.

B. Circuit Analysis Techniques: How Students Apply Circuit Analysis Techniques

This theme draws together methods used by students in simplifying the circuit after their initial visual inspection.

Nodes

Participants' main challenge was recognizing that point A and point B had the same potential. This took differing amounts of time with some never making this realization, which hindered their ability to continue simplifying the circuit. Two examples:

Node A and B are the same, so you can almost cut out B and A altogether.

I think the voltages on point B and point A will be different if the resistor values [R1-R4] are different. Of course if they're the same it should be the same value.

Research literature in physics has several examples of students' misconceptions on the fundamental nature of voltage and current [15], [18], [31], so some participants struggling with this step is not unprecedented. It does indicate the importance in education of taking fundamental concepts and clearly indicating how they apply within circuit diagrams. Bodensiek, Sonntag, Glawe and Müller [32] reported positive results from constructing virtual and physical models to explain the properties of voltage and current in dc circuits, reporting that when series and parallel components were combined, participants became less confident in explaining the behavior of current and voltage.

To correct the misconceptions that participants displayed, the first step is for students and instructors to be aware of their existence. The DIRECT tool [16] uses circuit diagrams with combinations of batteries and bulbs to interrogate school and university students' misconceptions of current and voltage. A 20-item concept inventory followed by interviews [33] identified the importance of using both quantitative and qualitative tools to detect and understand held misconceptions. These diagnostics are designed to highlight misconceptions, not how circuit rearrangement may be linked to them.

Circuit Analysis Techniques

Students generally have a set of learned tools that they will use to simplify a circuit when they view a problem as complex. The specific tools used vary between participants, however, most referred to doing without thinking, or not knowing the terms for the methods they were using. Two examples:

[I use] mainly the potential divider rule, when I'm looking at more complex techniques like Thevenin and Norton. Umm and mesh and nodal analysis. Yeah, so normally ... when I'm doing um a mesh analysis problem, I, I tend to focus only on currents and sort of, um I never really realize potential divider rule, realize the use of the potential divider rule.

When it's stuff like this [circuit] and it's slightly more complicated as to what's actually happening, that's when I'd start, I'd start breaking out the mesh and nodal analysis.

While this can demonstrate a level of disciplinary fluency, the lack of clarity by participants naming their selection of an analysis tool based upon the parameters of the problem was of note. In these responses, the language of participants indicated name checking analysis methods from their studies without reference to the parameters of the problem. This practice reflects the analysis of examination paper responses by Fayyaz and Truemen [34], where they noted that students were applying techniques that they had memorized from other circuits and were failing to apply analysis tools correctly.

Error Checking

Participants were asked how they check their work for errors in a broader context. While methods were mixed, including some with no approach for checking, the use of software was the most common. The range of approaches utilized is presented here to illuminate the scope and interplay of different methods. PLECS and LTSpice are both software packages used frequently within the participants' degree programs. The following examples are from multiple participants:

I'd probably check one by one if each resistor and each connection is actually hooked up in the same way as the one in the image even though it doesn't look the same.

So first I'd double check I had all the components ... that would be the easiest thing to miss, so I'd say oh I don't see an R7 and that means somewhere I've probably missed an entire branch. I've used PLECS and LTSpice ... and they're useful, especially since they have their own tools to like fact check and maybe error check.

If I were to do Norton, or Thevenin, or mesh, or nodal, I would normally just check my equations, rather than checking the arrangement.

The simple answer would be just to design both the original circuit as is and with all the resistors of x values and then do one of my combined resistor value and double check, make sure everything checks out.

A lot of the time if I want to make a circuit … I draw it out and then kind of simulate it in my head, which uhh, I know some people, lecturers don't really like! But it seems to, it seems to be fairly reliable.

[I use] circuit simulations, I usually find them useful to just like quickly check if something works in the way I think it does.

> *If it was everyday life I would build the circuit without simplification in some kind of simulation software and then um probe it at points.*
>
> *I'm getting if you want to call it, more lazy and using PLECS for uhh analyzing even a small circuit like this because you can just put meters everywhere and it's very quick and easy, for me anyway.*
>
> *If I'm going to do that [use software for error checking], I got to, I've got to take into account that, hmm, not my rearranged circuit, I'd just put everything because the whole operation would be done by LTSpice.*

While a diverse range of approaches were employed, the majority rely on mechanicalistic, quantitative approaches to confirm answers, echoing the observations made during other parts of participant interviews.

V. VALIDITY AND TRANSFERABILITY

The researchers recognize that qualitative methods are less commonly used within the pedagogy of the discipline, so the following presents a discussion of validity and transferability within RTA.

Regarding sample size, the key question to be posed is: ‘does the data collected provide insight?’ [35], rather than seeking fully representative populations.

There is no consensus on sample sizes for qualitative methods; a review of 83 studies in computer information systems [36] found no agreement and recommended a sample of 15-30 participants, while at the same time acknowledging that this range would be smaller within the UK due to different research conventions. Qualitative studies within chemical engineering have used sample sizes of 15 [37], within physics sample sizes of 12 [20], and within software engineering, an experiment branch contained six participant interviews [38].

Discussions of the validity of a qualitative analysis are fundamentally different from methods employed in a quantitative analysis. A consideration of reliability removes the personal experiences of participants from the analysis. Instead the validity of various aspects is considered [39]:

Construct validity: Does the data collection measure succeed in measuring what it set out to? The aim was to understand student processes when rearranging a circuit diagram. The findings are valid for simple circuits, but may not be generalizable to more complex circuits.

Internal validity: Are findings from the study more likely to be due to an additional contributing factor? The circuits were kept simple to reduce cognitive overload, and participants were reassured that their process was important rather than their answer to support the elicitation of candid responses.

External validity: Can the results be generalized from the sample to a wider population? The findings presented here were recurrent themes amongst the participants and these have been linked to literature in these areas, therefore some external validity is posited.

This study provides conceptual generalizability. The question of validity should not be “how far do these responses represent typical views for the whole population of students?”, but instead “how far do these responses help us understand what is going on when students rearrange an unseen circuit diagram?”. The transferability is then up to the reader to consider, and is context specific: the circuit within this research is unlikely to be transferred, however, the core concepts of where students begin their solution, and their application of voltage and current rules as they understand them are likely applicable for many students within the readers’ institutions.

VI. CONCLUSIONS AND FUTURE WORK

Within this work, students’ voices were given prominence to describe their approaches during the process of rearranging a circuit diagram, giving unique insights into university-level education in electronic engineering from a student perspective.

This work has clearly highlighted a key challenge in engineering education, namely the overreliance of some students on pattern recognition to attempt to rearrange circuit problems. When addressing unfamiliar or unconventional circuit configurations, this created delays before progress to a solution could continue.

To support learners in developing adaptive circuit solution skills, academics need to equip students with analysis tools to understand the fundamental properties of current and voltage in both a qualitative and quantitative basis. They then need to empower students to use this understanding to resolve a range of problems, rather than using permutations of regularly seen layouts. The first step in implementation is the inclusion of unfamiliar or unconventional circuit formats into teaching materials to demonstrate the limits of pattern recognition and to support deeper level analysis. Once students develop confidence in this aspect, the inclusion of real-world scenarios as suggested by Espera and Pitterson [10] could enhance learners’ understanding.

Students preferred a mechanicalistic approach to circuits with component values over symbols. This was mirrored by error checking methods where software was often deployed. This finding supports the recommendations in the literature that a greater emphasis on conceptual understanding of circuit properties can scaffold deeper comprehension and sense checking. Software is a valuable tool within the discipline, however, its use cases should be made clear by instructors to ensure it is deployed as an educational and analysis tool, discouraging its use as a method to quantitatively solve circuit problems without the need for conceptual understanding.

Future work will focus on narrower research questions with larger sample sizes to interrogate the effects seen within this research, employing a mixed-methods approach of qualitative and quantitative data.

ACKNOWLEDGEMENT

The authors would like to thank Dr Noel Murphy from the School of Electronic Engineering at Dublin City University for his assistance in proof-reading this manuscript.

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