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iJEP International Journal of Engineering Pedagogy

iJEP | eISSN: 2192-4880 | Vol. 14 No. 8 (2024) | OPEN ACCESS

https://doi.org/10.3991/ijep.v14i8.48319

PAPER

An Exploratory Qualitative Investigation into How Introductory Students Troubleshoot an Electronic Circuit

Pádraig Herbert(✉),
Tom O'Mahony

Munster Technological University, Cork, Ireland

padraig.herbert@mtu.ie

ABSTRACT

Troubleshooting is recognised to be a key laboratory learning objective within engineering education. However, little is known about how students taking introductory courses troubleshoot electronic circuits. The contribution of this study, therefore, is to use object-orientated focus groups with a think-aloud protocol to gather data while participants engage in the task of troubleshooting an electronic circuit. Content analysis was used to qualitatively analyse the gathered data based on a previously established cognitive task analysis (CTA) model. The findings, while limited by the sample size, indicate that participants tended to dive straight into the troubleshooting activity, and their troubleshooting process was mostly characterised by two phases of the CTA model, namely *test* along with *repair and evaluate*. Earlier phases of the process that involve specific actions, such as discerning the function of parts of the system, brainstorming causes and solutions, and developing a troubleshooting plan, received less attention. The primary implication is that formal troubleshooting instruction may need to be better embedded within introductory courses, though additional research is needed to validate this implication.

KEYWORDS

troubleshooting, electronic circuits, fault-finding, object-orientated focus group, think-aloud

1 INTRODUCTION

In engineering education, laboratories play a crucial role in supporting learning and developing professional competencies [1], [2]. Laboratories can take a variety of formats, including problem-orientated, face-to-face laboratories [3], virtual reality-based laboratories [4], remote laboratories [5], and low-cost laboratories have even been incorporated into large lecture-based classes [6]. Regardless of the laboratory mode, engineering laboratories are expected to address a range of laboratory learning objectives (LLO) [7]. Of interest to this paper, the description associated with LLO 5: Design includes 'testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements' [7, p. 127], while LLO 6: Learn from failure

Herbert, P., O'Mahony, T. (2024). An Exploratory Qualitative Investigation into How Introductory Students Troubleshoot an Electronic Circuit. *International Journal of Engineering Pedagogy (iJEP)*, 14(8), pp. 139–152. https://doi.org/10.3991/ijep.v14i8.48319

Article submitted 2024-02-01. Revision uploaded 2024-07-26. Final acceptance 2024-08-29.

relates to identifying 'unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineering effective solutions'. These LLO's enshrine the importance of developing engineering graduates' fault-finding or troubleshooting skills. While developing these skills is recognised to be important, engineering education research that is specifically focused on fault-finding or troubleshooting electronic circuits is almost non-existent [8].

This study therefore contributes to this under-researched topic by examining how undergraduate participants troubleshoot a malfunctioning electronic circuit using think-aloud, object-orientated focus groups. The study extends the research conducted by [8] by revealing that participants spend relatively little time in the early stages of the troubleshooting process and tend to focus on proposing potential solutions and performing diagnostic measurements. Hence, this exploratory study reveals some possible implications for practice. These implications are important, as a recent research within Electronic Engineering indicates that undergraduate students find troubleshooting or fault-finding electronic circuits independently a real challenge [9], [10]. Hence, identifying ways in which this skill can be enhanced is important, and additional research in this area is urgently needed.

2 TROUBLESHOOTING ELECTRONIC CIRCUITS

Troubleshooting is a systematic approach to the isolation of a fault in a system and the remediation of faulty component(s) to resolve the problem and can be applied to a variety of systems, from hardware to software to societal interactions to medical and psychological diagnoses [11]. Often the cause of the problem is not known; however, the solution state is known [12]. Troubleshooting consists of two modes: the cognitive task of solving the problem and the physical repair or replacement task [13]. To successfully troubleshoot an assigned circuit, learners need to have sufficient content knowledge and also need to know how and when to use laboratory equipment [13].

In [13], a CTA model was used to identify four distinct phases associated with the process of troubleshooting, where CTA is '*a family of methods used for studying and describing reasoning and knowledge*' [14, p. 3]. The model proposed by [13] begins with a *Formulate Problem Description* phase, the aim of which is to figure out exactly what the problem is, i.e., what elements are working and what is not. The second *generate causes* phase involves brainstorming to generate hypotheses relating to the malfunctioning device(s) either by drawing on existing expertise or reasoning skills supported by external documentation and/or exploratory measurements. In the third phase, *Test*, a formal strategy for testing the circuit should be defined, followed by measurements or checks to determine whether any of the hypotheses hold true. Example strategies include the *exhaustive strategy* where all possible faults are tested in a sequential fashion and *split-half*, which involves checking the circuit functionality at a midpoint to reduce the problem space by half [11]. When a fault is uncovered, the final phase, *repair and evaluate*, focuses on repairing the fault and returning the system to its normal operating state.

2.1 Electronic laboratories

Several studies have investigated learning within an electronic engineering laboratory environment [15], [16], [17], [18], [19]. One characteristic of much of the existing research is that it is predominantly quantitative in nature, with a reliance on structured data capture techniques such as student questionnaires, standardised MCQ tests, and evaluations of laboratory submissions. For example, [19] reports improved post-test grades following the introduction of a teaching method known as voltage tracking and division. Similarly, [16] reported improvements between pre- and post-test results when a circuit simulation application was used to support laboratory exercises. While this type of quantitative approach may evidence that the intervention has had some positive impact on learning, the nature of the data reveals little about how students go about learning. Hence, a quantitative approach will provide limited insight into the troubleshooting process or why learners might take certain actions.

Existing research that specifically focuses on troubleshooting electronic circuits is almost non-existent. For instance, in [18], the authors explore the potential of a mixed reality system to provide support for students in the design and development of electronic circuits. However, the paper focuses on describing the technology and does not discuss if it had any impact on students' ability to troubleshoot circuits. The extent to which students understand the overall objective of electronics laboratories was explored in [17], and their findings indicate a 'low level of understanding of the assigned tasks'. The research also revealed a direct relationship between task understanding and conceptual understanding. Again, however, the focus was not on troubleshooting.

In contrast, the companion articles [8] and [12] directly explore troubleshooting in an electronic engineering laboratory environment. The studies presented participants with a malfunctioning electronic circuit and asked pairs of students to troubleshoot the circuit and engage in a think-aloud protocol to simultaneously explain their actions. The study [8] is based on the CTA model [13], and the results revealed that each pair of students engaged in all four cognitive troubleshooting phases. Moreover, the approach adopted by each pair modelled a sensible troubleshooting process that started by trying to understand the presented circuit and making plans for how to test the circuit. Halfway through, pairs began suggesting and isolating faults via diagnostic measurements, and by the end, almost all pairs had successfully repaired the circuit. The troubleshooting activity was found to be quite non-linear and recursive. Based on the same student activity, [12] focused on the collaborative nature of the activity and how collaboration supported the individual students to make more sense of the troubleshooting activity by requiring individuals to explain their thinking, seek feedback on that thinking, and monitor each other's thinking.

2.2 The research gap

To the authors knowledge, only a single study has attempted to explore how undergraduate students troubleshoot an electronic circuit [8]. Hence, how learners troubleshoot electronic circuits in introductory courses is under researched. At the same time, troubleshooting plays a prominent role in engineering laboratory objectives [7]. Research exploring learning in online and remote environments suggests that students may experience particular difficulties troubleshooting electronic circuits [9], [10], and that these difficulties may be more pronounced in introductory courses [20]. Hence, exploring fully how students troubleshoot electronic circuits and subsequently developing strategies to enhance that activity are important to ensure that all graduates develop this key skill.

3 RESEARCH DESIGN AND METHOD

The specific research question adopted for this study was: How do engineering students taking introductory courses troubleshoot a faulty electronic circuit?

3.1 Participants

Given that it is not possible to unlearn something or return to an anthological position where one is not aware of something already known [21], learners, especially those who are troubleshooting circuits for the first time are best positioned, ontologically, to reveal how novices approach this task. Therefore, participants were recruited from the 1st year of the BEng. in Electronic Engineering and the 3rd year of the BEng. in Biomedical Engineering Degree at MTU. Both groups had been exposed to similar concepts within electronic engineering—though not the same modules, learning resources, or lecturers. Drawing from both programs widened the pool of potential applicants with the hope of acquiring a reasonable sample of 10 to 12 participants. All students in both years were invited to participate (N = 33), but only four, two from each program, volunteered.

3.2 Data collection

In the electronics laboratory, students frequently work in pairs—sometimes out of necessity due to limited resources and sometimes to provide peer support. Hence, using small focus groups rather than individual interviews aligns the data collection process with how students naturally troubleshoot in the laboratory. Furthermore, focus groups offer the advantage that they '*help to discover new aspects and information of one's research, as the participants own and contribute together much more and more diverse perspectives on the elected topic*' [22]. Bourne and Winstone advocate for activity or object-orientated focus groups, as the embedded activity can provide participants with an alternative way to respond or a concrete focus for discussions and may be more interesting and engaging for students. Greater levels of engagement can then '*elicit a more authentic student voice*' [23, p. 352].

The focus group design followed a published procedure [8] where the participants were presented with a laboratory sheet containing the schematic of a circuit along with the physical malfunctioning circuit that participants needed to troubleshoot. The participants were given some additional components and had access to an electronics workbench station consisting of a digital multimeter (to take measurements of current and voltage) and a benchtop power supply (to provide power to the circuit). The circuit was different from circuits that participants would have experienced in their laboratory experiences but drew on basic theoretical concepts familiar to all participants. The focus group began by explaining to participants the objective of the task and encouraging them to *think aloud* as they engaged with the troubleshooting task. The think-aloud protocol attempts to access the working memory portion of the human cognitive system by using the subjects own verbal protocol as data and is a commonly used thought process in qualitative research [24]. As described in [25], '*the course of the thought process can be inferred in considerable detail from thinking-aloud protocol*'. Each focus group was both audio and video recorded so that participants thinking via the think-aloud protocol, as well as their physical troubleshooting actions, could be authentically captured. The focus group concluded either after the participants had successfully returned the circuit to a functioning state or had run out of time. The maximum time allowed for the troubleshooting activity was 30 minutes.

3.3 Troubleshooting task

The participants were presented with a circuit diagram as shown in Figure 1, which presents the correct operational state of the circuit. The circuit presented to the participants was built on a breadboard in a faulty state (see Figure 2). Participants needed to diagnose and repair three faults. Fault one related to the power supply for the circuit, which was not connected. Furthermore, the benchtop power supply was set to zero voltage, zero current, with the DC output switch set to off. Fault two is related to resistors R1 and R3, which are different sizes, with R3 being larger to limit the current through the light emitting diode (LED) D3 and prevent it from lighting. In the physical circuit, the two resistors were swapped, hence LED D1 was off and LED D3 was on. Fault three related to the LED D4. LEDs have a polarity, i.e., it matters how they are connected relative to the power supply V1, and in this case the LED labelled D4 was placed on the breadboard in reverse polarity.

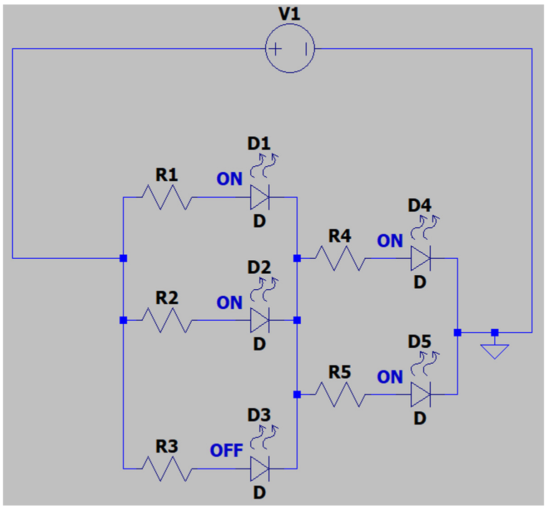

Fig. 1. Circuit diagram

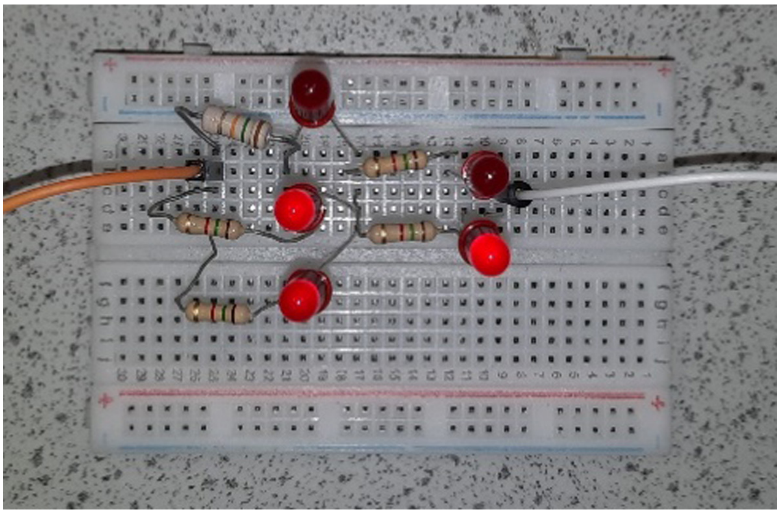

Fig. 2. Presented physical circuit with faults

3.4 Data analysis

The audio data was automatically transcribed, then edited and validated by the first researcher to generate an accurate transcription. These transcriptions were then pseudonymised. Given that prior research has confirmed the appropriateness of the CTA model, a deductive content analysis process [26] based on this framework was applied to make sense of this data. The predetermined codes were derived from [8] and are presented in Table 1 along with representative examples from the focus group transcriptions. Based on existing descriptions of this framework [8], [13] activities were coded as *formulate problem description* if they happened early on in the troubleshooting process, and given the relatively simple and visual nature of the task, the only expected formative measurement was to power up the circuit and observe what happens. Sections were coded as G3 if both participants engaged in a discussion, and therefore these are longer segments where participants are trying to understand what is happening. In contrast, segments coded as R1 are shorter and typically proposed by an individual. Both researchers independently coded the data and then compared and discussed codes to arrive at a consensus.

Table 1. Predetermined categories and codes that were derived from [8] and representative examples from focus group transcripts

Category	Code and Description	Representative Examples from Focus Group Transcripts
Formulate Problem Description	F1: Map circuit onto schematic and/or data sheet i.e., compare physical circuit with circuit diagram to verify that the physical circuit realises the schematic.	'I want to study the drawing a bit in relation to the to the breadboard.' 'We'll just follow it from the beginning … So, you go R1 into D1, and you have R2 to D2, you have R4 to D4 … .'
	F2: Discern function of systems, components i.e., ask 'How does the overall system work?' or recognise that the system consists of two parallel circuits.	'Three resistors here and two here. They're in parallel.' 'What does that button do again? Changes from what to what?'
	F3: Perform formative measurements e.g., power up the circuit and visually observe what is happening.	'Yeah, OK. OK, now you can see the LEDs are on and the one that D3 is on when it shouldn't be on. D1 is off when it should be on.'
Generate Causes	G1: Brainstorm potential causes or strategies i.e., engage in a distinct brainstorming session.	
	G2: Isolate subsystems as (mal)functioning e.g., identify the power supply as not delivering current.	'First check out the power supply is giving out any power?'
	G3: General discussion about causes or strategies i.e., discuss why the circuit is not functioning or how to approach the troubleshooting task. Both students would be involved.	Speaker 2 'So wouldn't you put the weaker resistors up here in the front or vice versa?' Speaker 4 'You see, if there's more resistance there, there will be less coming to here' … . Speaker 2 'So if we change this resistor here to match these ones. It should illuminate this one which will in turn illuminate this and then we can go from there.'
Test	T1: Make a plan or prioritise measurements i.e., explicitly state how they plan to troubleshoot the circuit.	'Thinking that we start with the ones that are supposed to be ON … and work from there … you get the ones that you want ON working.' 'We could start from the start and go from R1.'
	T2: Formulate expectations about measurements i.e., state what they expect prior to taking a measurement.	
	T3: Perform diagnostic measurements i.e., take a measurement or observation to help identify a problem.	'Checking the LED beside it and it's 1.7volts.' 'But we still are faced with the problem that D4 should be ON and it is OFF.'
Repair and Evaluate	RE1: Propose a potential solution.	'So, if we change this resistor here to match these ones.' 'Nothing is happening. So that must mean that … the diode in wrong.'
	RE2: Replace component(s).	'Take out that resistance and swap it with that one there.' 'I'm swapping around D3 and D4 just to eliminate the chances of a faulty … to test for a faulty LED.'
	RE3: Change circuit configuration e.g., rewire the circuit or remove components (not necessary).	'Can I just try something for a sec? I want to bypass this resistor here as a quick way just to check the LED.'
	RE4: Perform evaluative measurements i.e., perform a test or observation to confirm that a fault has been fixed.	Speaker 3 'OK, moment of truth. Turn it. Back on again.' Speaker 2 'And all the diodes are ON that should be ON and Diode 3 is OFF.'

4 RESULTS

Figures 3 and 4 present the coding results for the four cognitive troubleshooting tasks depicted against the timeline of the troubleshooting activity. The coloured bands light grey, dark grey, white, and back were used to represent the different troubleshooting phases: *Formulate problem description*, *Generate causes*, *Test*, and *Repair and evaluate*. Within each of these bands, the numbers correspond to the codes defined in Table 1. For example, considering Figure 3 and focusing on the *Repair and evaluate* phase, the numbers 1–4 correspond to the codes R1 to R4. Figures 2 and 3 clearly illustrate that focus group 1 (FG1) (biomedical engineering) took almost three times as long to return the circuit to an operational state as focus group 2 (FG2). In both cases, the nature of the troubleshooting activity was quite iterative and non-linear. Because of the longer timeframe required to complete the activity, FG1 generated more data and more codes. Normalising, so that the total number of codes for each focus group was equal to 10, and plotting the frequency of occurrence for each of the codes described in Table 1 generated Figure 5. Figure 5 illustrates that while the time taken to complete the troubleshooting task was different, the overall approach taken by both groups was broadly similar.

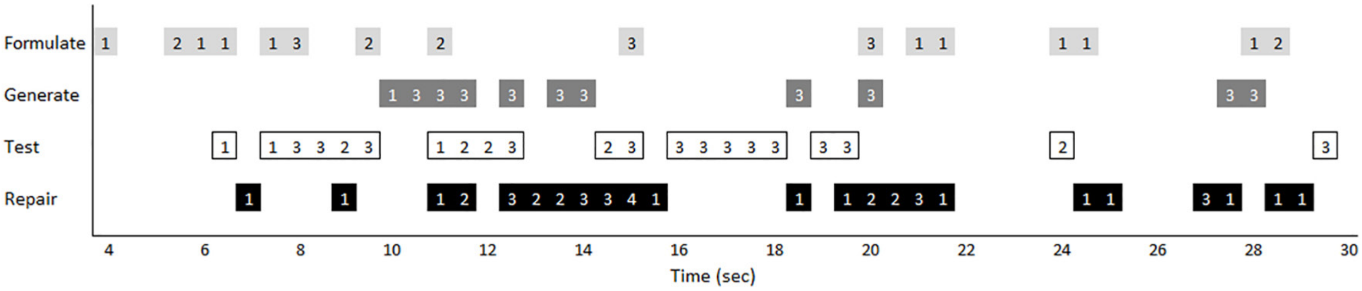

Fig. 3. Timeline of cognitive task analysis for focus group 1

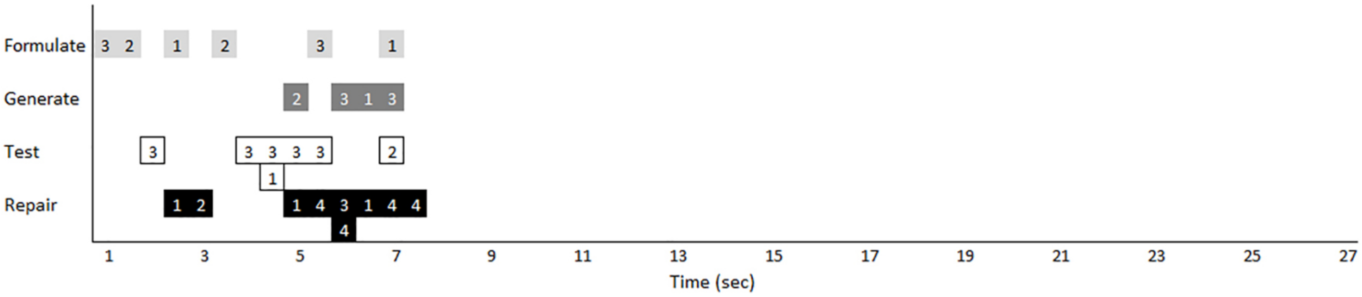

Fig. 4. Timeline of cognitive task analysis for focus group 2

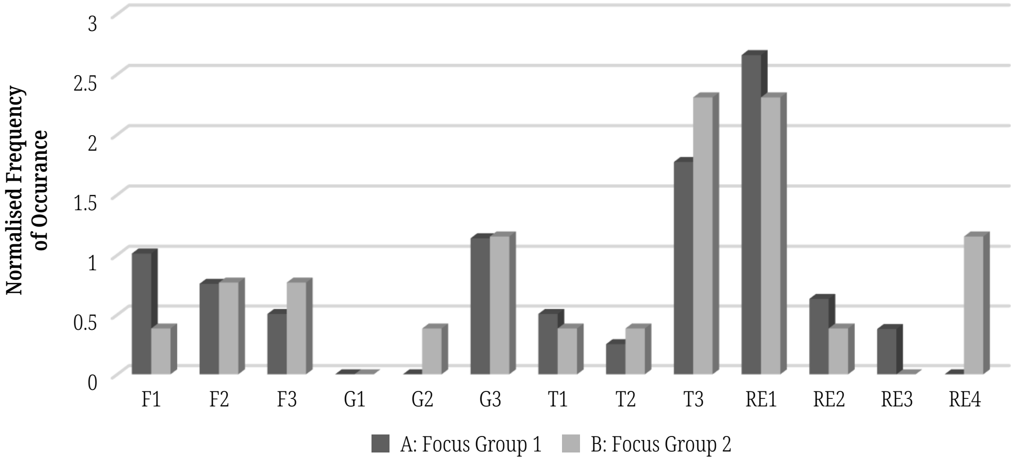

Fig. 5. Comparison of cognitive task activity between focus groups

4.1 Formulate problem description

Overall, both groups spent relatively less time in this phase than was spent on the *Test* or *Repair and Evaluate* phases. Both groups spent a little time orientating the physical circuit to the schematic, with FG1 explicitly doing this prior to engaging in any measurements. '*I want to study the drawing a bit in relation to the breadboard,*' while for FG2, it was more implicit, and after they had diagnosed and solved the LED polarity problem (Fault 3) with one member suggesting they check, '*Are they all on the same track?*' This orientation phase also posed challenges for FG1, and 20 minutes into the activity, they incorrectly identified that the physical circuit was wired incorrectly: '*Oh, I see the problem. How did I not see that? These resistors here are coming out of the wrong location*'. There was very little attempt to discern the function of the circuits (F2), and neither focus group provided an explicit explanation for how the circuit might work. There was some recognition of parallel circuits and of the impact of the resistors in front of the LEDs. '*The current limiting resistor was too high*' (FG2), and '*it'd say that we should be looking, maybe at putting our stronger resistor into D4. Because that should knock it down a bit, the current*' (FG1). FG1 initially demonstrated misconceptions about how parallel circuits work, believing that '*if we swap that resistor* [points to R1] *over to this side* [points to R3], *it will turn off this one* [points to D3], *but it will also effect this one here* [points to R1].' (FG1), and they were 24 minutes into the activity before this misconception was corrected.

> Participant 4: *'R5 though is being fed from your resistor'.*
> Participant 2: *'R5 has been fed from R3, R2, and R1. They're all linked, and in R4, it's been fed from R1, R2, and R3 as well. So R5 and R4 have no reason for the resistors to be different'.*

As this circuit was very visual—the LEDs either emitted light or they did not—the main formative measurement was to power up the circuit and observe whether the correct LEDs emitted light as per Figure 1, and both groups engaged with this activity.

4.2 Generate causes

Of the four phases in the troubleshooting process, this phase was the one that was least engaged with. Throughout the troubleshooting process, there was no evidence of an explicit brainstorming activity where both individuals were engaged with proposing a range of possible causes. On the contrary, 28 minutes into the activity, FG1 was prompted by the interviewer via the question '*What else could cause a LED not to illuminate?*' to engage in this type of activity, but FG1 persisted in proposing and testing singular solutions (R1) rather than brainstorming. Given the relatively simple nature of the troubleshooting activity, we would not have expected G2 to play a dominant role in the troubleshooting activity. The obvious subsystem was the power supply, which did have a fault associated with it, and this was explicitly identified by FG2 when they suggested to '*check the terminals from five volts to ground to see if there's any power being given in in the first place*' but somewhat implicitly by FG1 when they recommended to '*press the button at the bottom*'–the button being the function that switches the supply from an AC source to a DC one. Related to this phase, both groups engaged in discussions that were focused on understanding the faults and proposing solutions, and as evident from the timelines in Figures 3 and 4, this discussion was distributed throughout the duration of the troubleshooting activity.

4.3 Test

Only one of the two groups explicitly articulated a troubleshooting plan, with one member suggesting that '*we could start from the start and go from R1*' and the other member proposing an alternative strategy, which was to '*start with the ones that are supposed to be ON and work from there. If you get the ones that you want ON working first … So, if you get the rest of them working, you know you have an idea of where to go with D3, so for it not to work*'. Participants tended not to make predictions in relation to measurements. This might be because many of the measurements were visual observations, and the immediate nature of those observations makes articulating predictions more challenging. However, even when making physical measurements of voltage and resistance, none of the participants articulated what they expected to measure prior to measurement. As Figure 5 evidences, both focus groups frequently performed diagnostic measurements. Many of these measurements were observational, e.g., '*D1 is OFF when it should be ON*', and some were actual measurements of voltage and resistance using the multimeter instrument, e.g., '*touching the electrodes of the multimeter on each side of the LED to test for resistance*'.

4.4 Repair and evaluate

Along with T3 *perform diagnostic measurements*, R1 *propose a potential solution* was the most dominant code. Even within the first two minutes of the activity, both groups are proposing potential solutions: '*Would it just be a case of just disconnecting this?*' (FG1) and '*Nothing is happening … so that must mean that diodes are in the wrong [way]*' (FG2). In many cases, troubleshooting involved a rapid cycle that consisted of performing a diagnostic measurement (T3), proposing a potential solution (R1), testing that solution (R2 or R3), and then performing an evaluative measurement (R4), as illustrated by this example, which was just over a minute long (FG2).

> Participant 2: '*Check the terminals from five volts to ground to see if there's any power being given in in the first place*' [T3]
> Participant 1: '*OK*'
> Participant 2: '*Connected from the surface, and it's not …*'
> Participant 1: '*OK*'
> Participant 2: '*It could be plugged in wrong, so*' [R1]
> Participant 2: '*First check out the polarity*'. [T3]
> Participant 2: '*But … but it's not on … It was not on DC*'. [R1]
> Participant 2: '*Turn the power supply on from AC to DC*'. [R2]
> Participant 2: '*Yeah, OK. OK, now you can see the LEDs are ON and that the one D3 is ON when it shouldn't be. D1 is OFF when it should be ON*'. [R4 and then T3]

For this troubleshooting task, there was little need to engage with R3, and even though FG1 spent over two minutes (between t = 22 seconds and 24 seconds) rewiring the circuit, this was unnecessary and resulted from an incorrect diagnosis.

5 DISCUSSION

The troubleshooting process adopted by both groups focused on taking diagnostic measurements and proposing potential solutions. Neither group spent much time initially orientating themselves to the task, trying to understand the circuit and how it should operate, or agreeing to a formal or systematic troubleshooting approach. Instead, both groups tended to dive straight in and try to identify and fix the observed problems. Identifying this mostly ad-hoc approach to troubleshooting is important because other work has identified that strategic knowledge is an essential part of competent troubleshooting [11], [27]. Formal strategies are important because they can help reduce the problem space and hence make the troubleshooting process more effective [28]. Commonly adopted troubleshooting strategies include exhaustive, topographical, and split-half. While a topographical approach was proposed—'*we could start from the start and go from R1*' (FG1)—the group did not follow through on this and instead opted for a more heuristic approach. Given that the circuit consisted of two obvious subcircuits, a logical approach would have been to adopt the split-half strategy and, for example, get the subcircuit with the three resistors and LEDs in parallel working first and then the one with two resistors and LEDs—or vice versa. While the absence of a formal strategy did not appear to unduly impact troubleshooting effectiveness in this instance, it is likely that the ad-hoc strategies adopted would become ineffective when presented with larger or more challenging troubleshooting problems.

Coupled with the absence of a formal troubleshooting strategy, participants did not initially attempt to develop a shared understanding for how the circuit was supposed to work or the purpose of specific components. While participants clearly understood what the circuit was supposed to do—i.e., which LEDs were to be ON and which were to be OFF—how the circuit operated to achieve this was not initially discussed. It is possible that individuals understood how the circuit was to operate, and this is more likely to apply to those individuals in FG2. Although younger (first year), perhaps because their discipline area was electronic engineering, they appeared to have a slightly stronger knowledge base, which supported their troubleshooting activity. For example, they almost immediately proposed that the LED might be incorrectly connected, demonstrating their conceptual understanding that LEDs have polarity. In contrast, and as stated in the results, FG1 were 24 minutes into the activity before this group arrived at a shared understanding for how parallel circuits work. The more limited system and disciplinary knowledge demonstrated by FG1 thwarted their troubleshooting efforts and may account for the longer time taken to complete the troubleshooting task.

The troubleshooting activity reported here can be compared with [8], where the authors report that 'all eight pairs [of students] engaged in all four cognitive troubleshooting tasks'. The timelines presented in [8] demonstrate that seven of the pairs spent the first 10 minutes of the activity alternating between the phases *Formulate Problem Description* and *Test*. There is also clear evidence of participants spending significant amounts of time during the second half of the troubleshooting activity in the phase *Generate Causes*. Hence, compared to our findings, the participants in [8] adopted a much more structured and systematic approach to the troubleshooting activity. This difference may be related to the fact that all of the participants in [8] were third-year students who, by that stage, had developed troubleshooting strategies or the more challenging nature of the troubleshooting task, which might have demanded a more structured approach. In contrast, half of our participants were first-year students, while the simpler and more visual nature of the troubleshooting task might have prompted a more ad hoc approach.

The main implication from this study is that there may be a greater need to formally teach engineering students how to troubleshoot and that the CTA model [13] might form a useful starting point to frame the troubleshooting process. We would contend that students receive very little formal instruction on how to troubleshoot. In their course description, [8] comment that there '*is no formal instruction about troubleshooting in either course; instead, discussion about troubleshooting is limited to impromptu conversations between students and instructors in response to problems that inevitably arise during lab*'. This heuristic approach to teaching troubleshooting is also common within our university across the two programs Electronic Engineering and Biomedical Engineering that are the focus of this study. It is therefore perhaps not surprising that studies have reported that students struggle to troubleshoot, especially when asked to do so independently [9], [10]. Hence, we would suggest that formal troubleshooting instruction may need to be better embedded within engineering education. One approach to doing that might be to present students with faulty systems, akin to the approach adopted here, and encourage students to utilise the CTA model as they work through the troubleshooting task. As they troubleshoot, students should be encouraged to think aloud and make explicit their troubleshooting strategies, their understanding of the system, along with their assumptions as they proceed through the task. Making some of what is normally tacit knowledge explicit should help develop these essential skills.

Our findings are limited by the small sample size, and while participants were drawn from two different engineering programs, they were from the same institution. Hence, both the sample size and singular context limit any possibility to generalize. In some ways, our findings contrast with those in [8], which mostly suggests that additional research is needed to further explore this topic.

6 CONCLUSION

This study applied the CTA model [13] to explore how participants troubleshoot electronic circuits. In the context of the troubleshooting activity, the participants can be regarded as novices, and therefore the study examines how novices troubleshoot electronic circuits. The findings, while limited by the sample size, indicate that these participants focused on two phases of the framework, namely *Test* along with *Repair and evaluate*. The limited attention given by participants to the two-preceding phase—*Formulate problem description* and *Generate causes*—suggests that more should be done to embed formal troubleshooting instruction within engineering education, though further research is required to validate this conclusion. Given the limited empirical research exploring troubleshooting with electronic engineering, coupled with the different findings revealed by this study compared with [8], we strongly recommend that additional research should empirically explore how engineers develop troubleshooting skills.

7 FUNDING ACKNOWLEDGEMENT

This study was part-funded by the Irish Higher Education Authority Technological University Fund and Munster Technological University.

8 ETHICAL APPROVAL

Ethical approval to conduct this study was received from the Human Research Ethics Committee at the university (Approval No: MTU-TLU-HREC-MR-33-A).

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10 AUTHORS

Pádraig Herbert B.Eng., M.Sc., MA, is a Lecturer in the Dept. of Mechanical, Biomedical & Manufacturing Engineering at Munster Technological University.

He has completed an MA in Teaching and Learning at MTU, and is currently also affiliated with the Tyndall Institute at University College Cork where he is pursuing a PhD. His research interests include physiological measurement, health technology management and more progressive teaching and learning practice in Engineering (E-mail: padraig.herbert@mtu.ie; ORCID: https://orcid.org/0009-0003-5465-4202).

Tom O'Mahony B.Eng., M.Eng., PhD, is affiliated with the Teaching and Learning Unit (TLU) and the Dept. of Electrical and Electronic Engineering at Munster Technological University. He is the Principal Investigator for the Teaching, Learning Assessment and Student Engagement (TLASE) Research Laboratory at MTU. His research interests include active learning, especially flipped, project and problem-based learning, assessment and feedback, and engineering education. Tom has over 50 peer-reviewed publications and peer-reviews for several educational research journals (E-mail: tom.omahony@mtu.ie; ORCID: https://orcid.org/0000-0002-0658-5797).