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Troubleshooting in Engineering Education: A Systematic Literature Review

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Abstract

This full-length theory paper reports on the results of a systematic review of the literature related to troubleshooting in engineering education. Troubleshooting is a vital problem-solving skill for successful engineering practice in many disciplines, and various studies have been conducted to investigate different aspects of student troubleshooting in educational contexts. In this paper, we synthesize and present findings on the landscape of research about troubleshooting in science and engineering education contexts. Then, based on that, we identify apparent gaps in the literature, provide suggestions for future research in this area, and discuss implications for instructional design that seeks to implement troubleshooting in undergraduate engineering settings. This paper intends to supplement and update prior reviews of empirical troubleshooting research – namely, the ones conducted by Morris and Rouse in 1985 and by Rivera-Reyes and Boyles in 2013.

This paper focuses on empirical studies related to troubleshooting in science and engineering education, as well as research papers that describe curricular troubleshooting interventions. This literature review was conducted systematically by following the PRISMA 2020 guidelines using the Covidence literature review platform. The information sources we searched to identify troubleshooting studies included search engines, digital libraries, and databases such as: Google Scholar, Engineering Village (Compendex and Inspec), ERIC, Education Source (EBSCO), IEEE Xplore, ASEE PEER, JSTOR, and SpringerLink. We limited the scope of this review to papers published from 1980 to 2024. Documents that focus solely on troubleshooting theory or serve as technical troubleshooting guides, training manuals, or otherwise explain how to maintain/repair a specific technical system, device, product, or service were excluded. Searching yielded an initial set of 453 papers, which were filtered using those criteria, resulting in 52 papers retained, which we then extracted relevant information from and characterized.

Analysis of retained papers considered: how researchers define troubleshooting (both as a problem typology and problem-solving process); how they ground it in theory (if any); the ways it has been implemented and studied in educational contexts; which aspects of it have been empirically investigated; which contexts, participants, and data types/collection methods have been involved in studies; and specific metrics used for evaluating student troubleshooting skills and performance. Four of our findings stand out most. First, there is a need to study student troubleshooting in multiple engineering disciplines, since the majority of studies in this area have been conducted in the context of electrical engineering and closely related fields. Second, there is a need to study undergraduate students' troubleshooting *processes* more granularly – namely, the strategies and approaches they use to attempt/solve troubleshooting problems, specific difficulties they might encounter while troubleshooting, and stages of the troubleshooting process they may struggle with most. Third, there is a general lack of grounding/framing in established and relevant troubleshooting theory among papers we considered. Fourth, future studies (and instructional implementation) should utilize more holistic methods for assessing students' troubleshooting skills that provide more insight into their proficiencies and deficiencies – not just whether they could solve the problem or not, how many they could solve, or the time it took them to do so.

Keywords: troubleshooting, problem-solving, engineering education, systematic literature review, PRISMA 2020, Covidence

Introduction and Research Purpose

Troubleshooting is a crucial problem-solving skill not only for people in everyday life [1], but especially for practicing engineers. The ability to effectively troubleshoot problems is a vital part of good engineering practice, and it is essential that engineers be proficient in this skill. Moreover, troubleshooting problems are one of the most common types of problems that professional engineers in all fields encounter [2], and they must frequently engage in the troubleshooting process to successfully solve them. These troubleshooting problems inevitably arise in all facets of required engineering duties across disciplines, and they can vary widely in terms of context, scope, complexity, structuredness, and solutions. Since problem solving is perhaps the most essential competency of practicing engineers [3], engineering and troubleshooting go hand in hand; in many ways, being a good engineer *means* being a good troubleshooter. Capable engineers must be able to diagnose and solve problems that arise within existing devices, structures, processes, and systems. We depend on engineers who know how to troubleshoot effectively to design, maintain, and repair the critical systems that we all rely on.

Because troubleshooting is such an important skill for engineers to be proficient in, it is equally important that aspiring engineers learn to troubleshoot effectively. It is crucial that engineering students are given the opportunity to encounter troubleshooting problems and practice solving them to develop this skill during their education or training, before they graduate and transition to the workforce. Toward this end, a variety of research has been conducted on many different aspects of troubleshooting in educational and technical training settings. For example, studies have investigated ideas such as: methods to teach students how to troubleshoot more effectively [4]; using digital/software tools or intelligent tutors to simulate troubleshooting scenarios for students [5]; examinations of student troubleshooting strategies and techniques for solving said problems [6], [7]; using troubleshooting exercises as a vehicle for students to learn specific technical concepts and skills (akin to problem-based learning) [8]; and the design and implementation of class or laboratory exercises, projects, or activities focused on troubleshooting [9], [10], just to name a few.

This paper synthesizes and presents findings of a systematic review of the research literature surrounding troubleshooting in engineering/technical education contexts. More specifically, the purpose of this paper is to characterize the landscape of papers that describe curricular troubleshooting interventions and empirical studies that have been conducted to investigate different aspects of student troubleshooting, which involve a variety of goals, participants, contexts, theoretical frameworks, data types and collection methods, and troubleshooting assessment metrics. Based on that information, we identify apparent gaps in the literature, provide suggestions for future research in this area, and discuss implications for instructional design that seeks to implement troubleshooting exercises in undergraduate engineering settings. This paper intends to supplement and update prior reviews of empirical troubleshooting research – namely, the ones conducted by Morris and Rouse in 1985 [11] and by Rivera-Reyes and Boyles in 2013 [12].

Literature Review Methodology and Procedure

Inclusion/Exclusion Criteria for Literature Search

We conducted a systematic literature search to identify and collect published research papers related to troubleshooting in science and engineering education contexts, and we did so by following the PRISMA 2020 guidelines [13]. We limited the scope of this review to include papers published from 1980 to 2024. We included empirical studies on the topic, as well as research papers that describe curricular troubleshooting interventions. For studies which focused on student participants, we only considered those which included undergraduate-level students (or higher), not K-12 students.

Moreover, for the purposes of this literature review, we intentionally excluded any documents that focus solely on troubleshooting theory, as well as any that serve as technical troubleshooting guides, training manuals, or otherwise explain how to maintain or repair a specific technical system, device, process, or service. Additionally, we excluded any research that focuses on debugging, which is a specific form of troubleshooting in computer science and software engineering contexts with its own universe of literature. Lastly, we also excluded any research that studies the use of correct or incorrect worked examples – so-called "erroneous examples" – in science and engineering education contexts. While learning from erroneous examples is somewhat related to the troubleshooting process, it is distinctly different in one crucial way; it usually does not require students to identify the fault in a given system, diagnose or explain the cause for it, and generate, implement, and verify solutions to correct it. Instead, studying erroneous examples only demonstrates to students what is wrong in a certain situation or procedure, and what should be done differently. While that is certainly valuable for understanding technical concepts and their applications, those steps that are left out are critical parts of the troubleshooting process [14], [15], [16], and it is essential that students be the ones to attempt those steps themselves. So, studies about erroneous examples did not qualify as troubleshooting for our review.

Title/Abstract Screening and Full Text Review

With those inclusion/exclusion criteria established, the information sources we searched to identify troubleshooting research literature included search engines, digital libraries, and databases such as: Google Scholar, Engineering Village (Compendex and Inspec), ERIC, Education Source (EBSCO), IEEE Xplore, ASEE PEER, JSTOR, and SpringerLink (Wiley). We used different combinations of the word "troubleshooting" with the following search terms: "education", "engineering education", "research", "undergraduate students" or "college students", "process", "teaching", "training", "learning", "method", "transfer", and "skill." For transparency, a few examples of complete search strings we used would be "troubleshooting engineering education," "troubleshooting undergraduate students," or "troubleshooting process teaching learning." Search logistics varied slightly by databases and interfaces, but in general, we searched using combinations of terms in this manner without modifying any fields or parameters, and without setting any filters. After iterating on combinations of search terms and procedures, we found that this strategy captured the broadest set of published documents possible.

We relied on those search terms to find and collect literature, and we included conference proceedings along with journal publications. Searching yielded an initial set of 453 total papers, which we imported into the Covidence literature review platform (https://app.covidence.org/) to remove duplicates and allow two different researchers to independently review and assess each item. Based on our specific inclusion/exclusion criteria and the purposes of our review, both researchers screened titles and abstracts of collected documents, then further filtered them by examining their full texts, which resulted in net 52 papers retained for this review. See Figure 1 for a flowchart overview of the searching, screening, and full text review process.

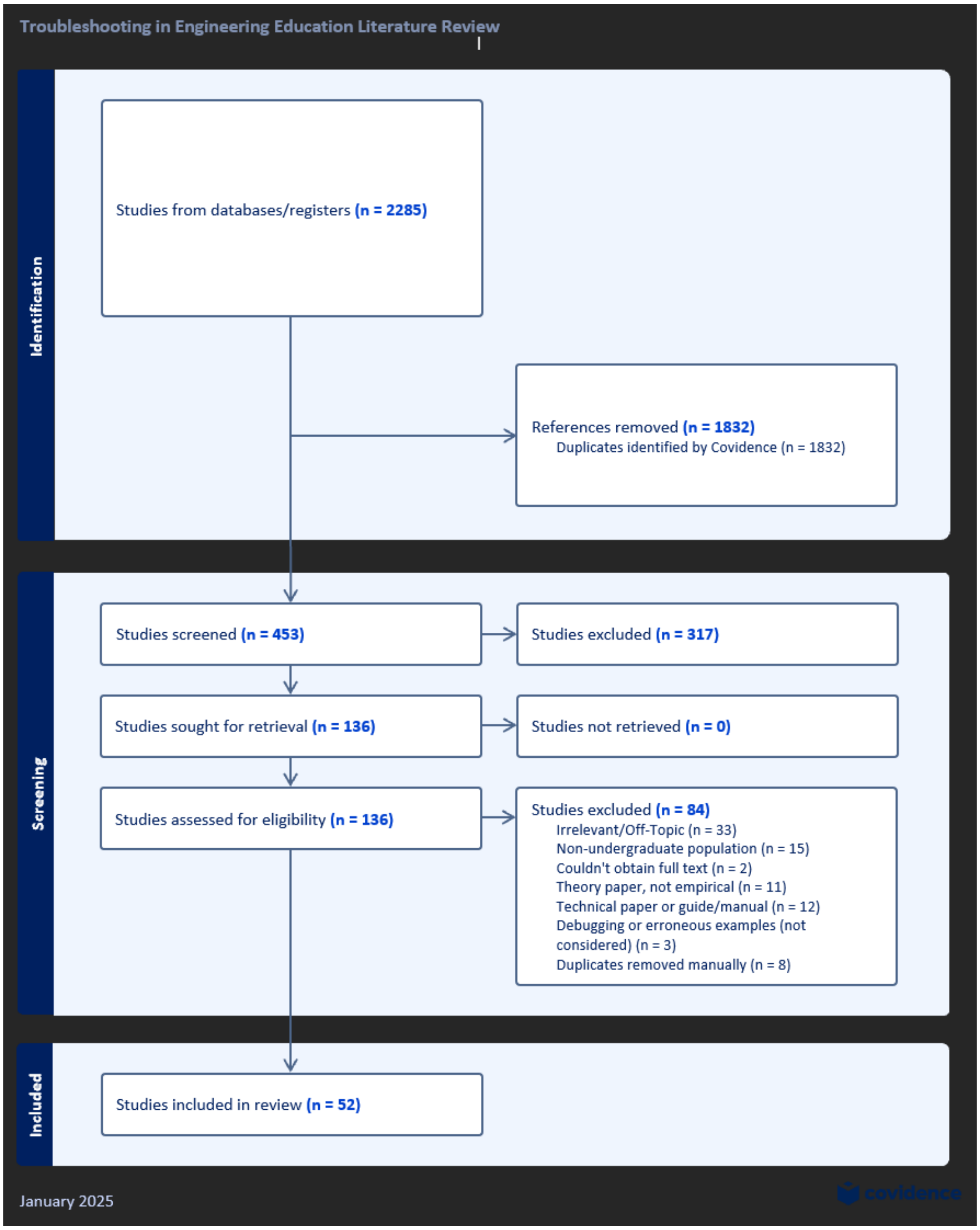

Figure 1. PRISMA flowchart of literature review process

Data Extraction

After the surviving set of 52 documents was reached, we created an extraction tool/template within the Covidence platform to extract relevant information from the remaining papers that would allow us to appropriately characterize groups of troubleshooting literature. The extraction criteria are shown in Table 1. The initial criteria identified at the outset of this study (i.e., prior to database searching) included engineering discipline/field, participants (who and how many), theoretical frameworks, and data types and collection methods. As we conducted full text reviews, additional criteria emerged as potentially valuable and were added to the extraction template. These additional criteria include the type of study (qualitative, quantitative, mixed-methods); its focus, purpose, and/or objective; and the mode of interaction of participants (usually students) doing troubleshooting in each study (if applicable). For example, certain studies focused on evaluating students' troubleshooting performance under certain conditions (e.g., think-aloud paired problem-solving) or after some kind of learning intervention (e.g., teaching students how to troubleshoot in some technical context). In contrast, other studies focused more on describing and testing some kind of digital software tool, framework, simulator, or intelligent tutor/assistant designed to facilitate students troubleshooting experiences and help them troubleshoot more effectively.

Table 1. Framework for data extraction

Engineering Discipline/Field Context	Electrical Mechanical Aviation/Aerospace Agricultural Chemical Biomedical Naval/Marine Other
Focus, Purpose, or Objective of Study	Learning Outcome or Instructional Intervention: Teaching troubleshooting practices (e.g., heuristics, strategies, process, etc…) Curricular Description (of a troubleshooting class, assignment, project, or exercise) Troubleshooting-Based Learning: Using troubleshooting as the vehicle for students to learn other, related conceptual/domain knowledge (analogous to PBL) Expert vs. Novice Comparison (of strategies, processes, practices, etc…) Digital tool, tutor, assistant, or simulator for troubleshooting Other
Participants	Students – First Year (undergrad) Students – other years (undergrad) Experts/Practitioners (real-world/industry) Instructors/Faculty N/A (no study or empirical part vague/unspecified)
TS Interaction Mode	Physical/Direct Virtual/Simulated/Remote Hybrid Other or N/A
Theoretical Frameworks	Troubleshooting and/or Problem Solving Learning/Pedagogy Metacognition/Reflection Other None/Unclear
Study Design	Qualitative Quantitative Mixed-Methods Other or N/A
Data Types & Collection Methods	Survey, Questionnaire, or Inventory Artifact Analysis Think-Aloud Protocol Observations Interviews Conceptual Test/Exam Scores (quant) Correct/Incorrect Solutions, Number of Faults Fixed, or Time to Solve (quant) Other or N/A
Metrics for Assessing Troubleshooting Goal/Outcome	Performance/product – troubleshooting success outcome (problem solved or not) Performance/product – troubleshooting success outcome (completion time) Learning process outcome (e.g., gained conceptual/domain knowledge, learned new troubleshooting strategies, improved at parts of troubleshooting process, etc...) Digital tutor, tool, simulator, or assistant effectiveness demonstrated successfully Troubleshooting class, assignment, project, or exercise effectiveness demonstrated successfully Other or N/A

Both researchers independently reviewed and extracted data from every troubleshooting paper in the set, marking and categorizing each one according to the extraction template criteria, as well as memoing notes to add details and record important information for later analysis. When including or excluding papers during title/abstract screening and full text review, as well as during data extraction and categorization, Covidence flagged all conflicts present among researchers' decisions. Both reviewers subsequently discussed and resolved all discrepancies to reach consensus on the final extracted data for every item. This is consistent with collaborative qualitative analysis practices to ensure consistency and inter-rater reliability [17], [18], [19]. Results of the extraction process are reported in terms of descriptive statistics and qualitative characterizations in the next section.

Results

We present overall descriptive statistics and general metrics representative of the landscape of research papers about troubleshooting in science and engineering education. Findings are grouped by data extraction criteria from Table 1.

Disciplines, Participants, Theoretical Grounding, and Study Designs

As it relates to discipline/field (Figure 3), the majority of papers report on studies that occurred in electrical (and computer) engineering contexts (50%), mostly in circuits, electronics, and embedded systems, with a few in network systems and information technology (IT) as well. Several papers reported on studies that occurred in mechanical (12%) and naval/marine (12%) engineering contexts. The few remaining papers reported on studies that occurred in chemical (10%), biomedical (6%), agricultural (6%), and aviation/aerospace (2%) engineering contexts. Most papers' study participants (Figure 4) were undergraduate-level students (68%), whereas a few studies targeted engineering practitioners in industry (13%) or engineering instructors/faculty (4%). Nineteen percent of papers either were unclear on participants or lacked an empirical study component altogether.

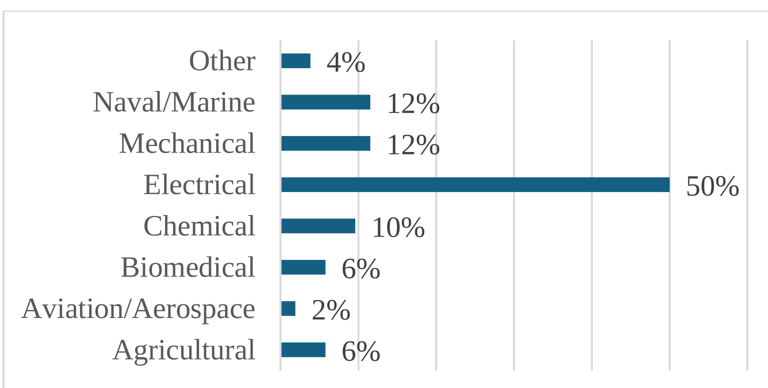

Figure 3. Engineering discipline/field of troubleshooting papers

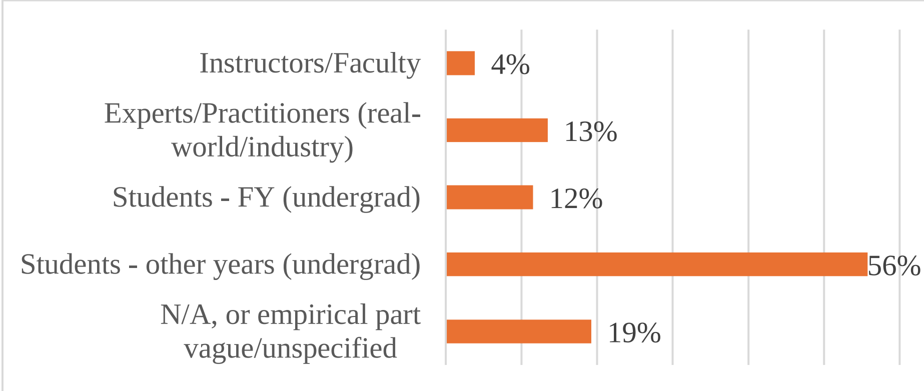

Figure 4. Participants of troubleshooting studies

For theoretical grounding (Figure 5), across all troubleshooting papers (whether they included an empirical study component or not), most of them (60%) grounded their work in some established troubleshooting or problem-solving theory. The most comprehensive and widely-cited among them included: 1) Johnson's Technical Troubleshooting Model [14], [20], 2) Jonassen's catalog of problem typologies and design theory of problem solving [15], [21], 3) Ross & Orr's DECSAR troubleshooting method [22], and 4) Schaafstal & Schraagen's task analysis troubleshooting approach [16]. Other subsets of papers framed their work on troubleshooting using a mix of meta/cognition, reflection, learning, and pedagogy theories. However, one-third (33%) of all troubleshooting research papers we considered did not ground or frame their work in any relevant theories of troubleshooting, general problem solving, metacognition, or learning. Moreover, there were a variety of study design types (i.e., quantitative, qualitative, or mixed-methods) present among troubleshooting papers; however, about 19% of them did not include any empirical study component (Figure 6).

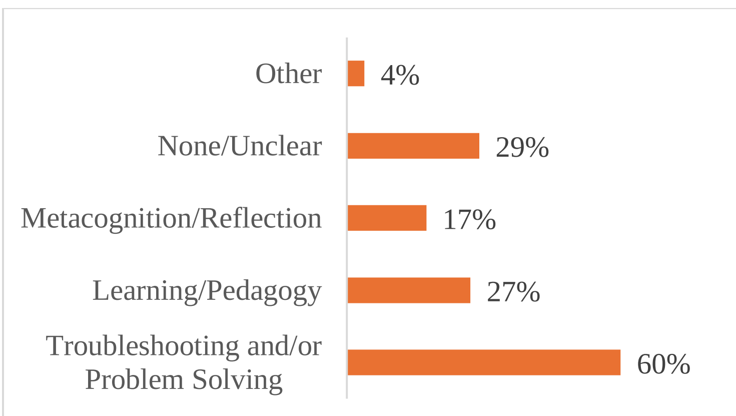

Figure 5. Theoretical frameworks of troubleshooting papers

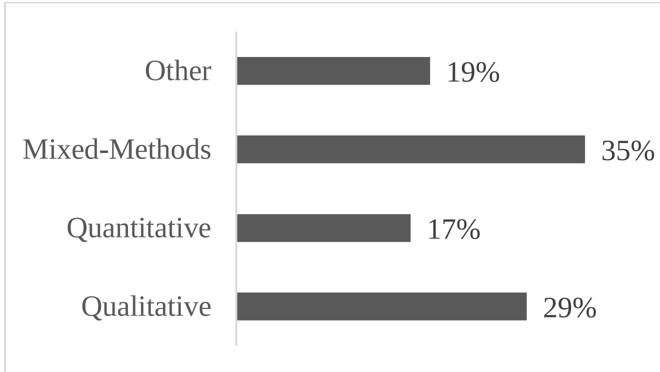

Figure 6. Study design types of troubleshooting papers

Focus/Objective, Data Types, and Collection Methods

Next, we found that the purpose or objective of reviewed papers broadly fit into several thematic categories, which are shown in Figure 7. To elaborate, "TS Intervention" (46%) refers to papers whose main purpose is to present some classroom intervention designed to teach students effective troubleshooting strategies or improve students' troubleshooting skills/performance, which is also assessed in some way via empirical methods after it is implemented. Compare this to "Curricular Description Only" papers (29%), which only describe some sort of class or lab activity, exercise, assignment, experiment, or project designed to allow students to practice their troubleshooting skills and engage in the troubleshooting process (e.g., [9], [23], [24]). Those papers lack a study component; they do not assess the effectiveness of their proposed curricular interventions on student troubleshooting abilities using any empirical procedures or data. "TS Simulator" (25%) refers to studies that focus on some kind of digital/software tool, system, platform, or intelligent tutor/assistant designed to simulate *virtual* troubleshooting problems and assist students with the troubleshooting process as they attempt to solve them. "Novice-Expert Characterization" (25%) refers to studies whose purpose is to document and analyze the strategies, techniques, decisions, and methods that novices (i.e., undergraduate engineering students) or experts (i.e., practicing engineers in industry, or engineering instructors) use when trying to solve troubleshooting problems. Lastly, "TS-BL" (10%), which stands for "troubleshooting-based learning" as we have termed it here, refers to studies that are analogous to problem-based learning (PBL) ones – i.e., studies that investigate (and empirically assess) the use of troubleshooting as a vehicle for students to learn *other* technical concepts and skills, not necessarily the skill or process of troubleshooting itself.

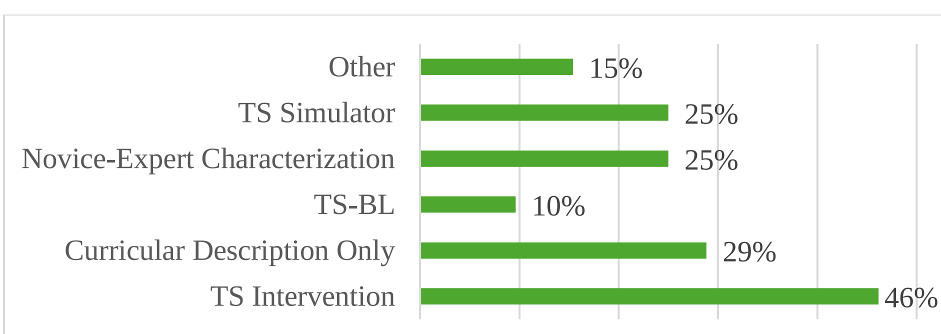

Figure 7. Focus, purpose, or objective of troubleshooting papers

For the subset of troubleshooting papers that included an empirical study, the data types and collection methods used (Figure 8) naturally varied depending on the purpose or goal of certain studies, out of the ones mentioned above. Overall, the most notable data collection methods used were: recording whether or not students successfully corrected faults in given troubleshooting problems, and the time it took them to correct faults, if they were able to (31%); conceptual exams (54%); surveys, questionnaires, or inventories (46%); and think-aloud protocols (21%). Lastly, in concert with the data types and collection methods used across troubleshooting studies, the specific metrics (Figure 9) used to assess desired aspects of troubleshooting also varied depending on the purpose or goal of each study. But in general, the most notable troubleshooting assessment metrics considered by studies in the paper set included: 1) students' troubleshooting performance – i.e., their ability to successfully correct faults (52%) and their efficiency in doing so, if they were able to (25%); 2) whether students improved at some step of the troubleshooting process or showed gain in conceptual knowledge from engaging with troubleshooting problems (40%); and 3) demonstrating the effectiveness of a particular curricular intervention (19%) or a virtual tool/assistant (15%) at improving students' troubleshooting abilities. However, most studies that were interested in the latter two metrics relied largely on quantitative data to prove effectiveness – namely, conceptual exams, number of faults corrected successfully, and the time taken to do so.

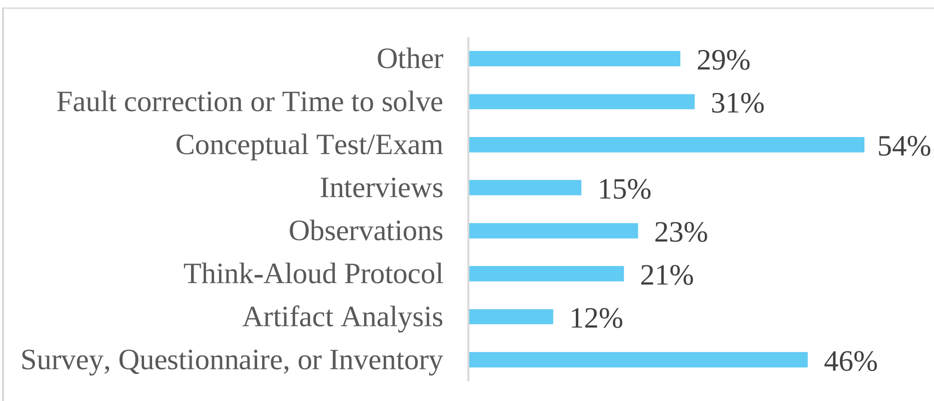

Figure 8. Data types and collection methods used in troubleshooting studies

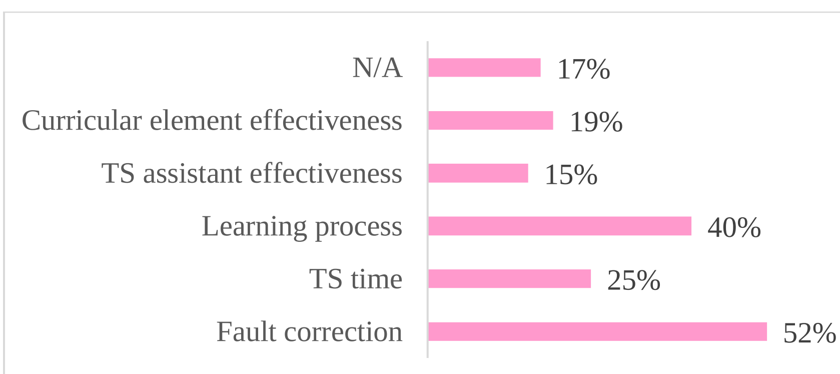

Figure 9. Desired troubleshooting assessment metrics of papers, if applicable

Discussion and Implications

Based on the data we have collected from reviewing the landscape of research literature on troubleshooting in science and engineering education contexts, four of our findings stand out most. First, there appears to be a relatively small number of published research papers in this area overall. This lack of literature indicates that there is much potential for future research work on this topic that investigates a variety of different aspects of troubleshooting. Especially when you consider that a subset of reviewed papers lack an empirical component (the twenty-nine percent of papers that focus on curricular descriptions only), the number of actual troubleshooting *studies* is even smaller.

Further, future work should investigate student troubleshooting or develop curricular interventions in multiple engineering disciplines, since the majority of published papers in this area are in the context of electrical engineering and/or closely related fields (e.g., [25], [26], [27]). There are scarcely any troubleshooting studies or curricular descriptions in any of the other engineering disciplines. Since troubleshooting is an important problem and skill that extends to all engineering domains [2], there is ample opportunity for more cross-disciplinary research on troubleshooting in education. We speculate that one reason for this disciplinary silo is that electrical engineering courses and contexts lend themselves more readily to creating troubleshooting problems for students to engage with. For example, many troubleshooting papers use circuits classes, exercises, and simulators to create troubleshooting scenarios for participants to practice [28], [29], [30]. It is relatively easy, cost-effective, logistically simple, and scalable to present multiple students with a given circuit that has one or more faulty components intentionally placed into it for them to try and identify, test, diagnose, fix, and verify. However, more research needs to be conducted on student troubleshooting in other engineering classes and contexts, since troubleshooting is a crucial skill for practicing engineers across disciplines, not just electrical engineers. The same goes for instructional implementation; authentic, hands-on troubleshooting problems, exercises, scenarios, projects, and equipment should be integrated into all undergraduate engineering settings to give students in all disciplines the opportunity to develop this vital skill, not just electrical engineering classes.

Second, future studies should investigate undergraduate students' troubleshooting *processes* more granularly – in particular, the strategies and techniques they use to attempt/solve troubleshooting problems; their thoughts, reasoning, and decision-making while troubleshooting; specific challenges they might encounter; and stages of the troubleshooting process they may struggle with most. It is also worth examining whether students' approaches match with known troubleshooting strategies and theoretical processes, or how they align with various learning or cognitive theories, for the sake of improving troubleshooting instruction. Few existing studies to date focus specifically on that [6], [7], [31], [32], [33], which is evidenced by only a portion of the twenty-five percent of total papers whose purpose was "Novice-Expert Characterization," as well as a portion of the forty percent of total papers that looked at students' "Learning Processes" as the metric of interest. Otherwise, most other troubleshooting studies do not examine students' processes or discuss their strategies and proficiencies/deficiencies at all. We argue that this is a promising niche of troubleshooting education research that remains unexplored that could uncover valuable insights into more effective ways to teach engineering students how to become better troubleshooters.

Third, there is a general lack of grounding in established and relevant troubleshooting theory among papers we considered (33% of total), not only in many of the studies in our paper set, but in many of the curricular description papers as well. Regarding existing studies, their own ad hoc explanations of the troubleshooting process, and descriptions of troubleshooting problems, are not necessarily incorrect according to theory and intuition. However, explicitly framing future work with established troubleshooting theory will likely increase the rigor and quality of research in this area. A common framework would enable researchers to discuss troubleshooting more consistently and allow more meaningful comparison of findings across different studies in the future.

The same can be said for troubleshooting instructional implementation, too. Existing curricular interventions are a good first step towards integrating troubleshooting experiences into various engineering course structures. However, grounding the design of these interventions in established troubleshooting theory, as well as the findings of relevant troubleshooting studies, may result in more complete and robust problems, activities, and feedback for undergraduate engineering students. For example, if instructors create troubleshooting problems and exercises that are based in authentic, real-world contexts, students may be more motivated to meaningfully engage with them [6]. Moreover, novice troubleshooters tend to struggle most with sufficiently identifying and locating the problem within a given system [15], [20], and many troubleshooting strategies have been identified to assist with this critical step, which may be worth explicitly teaching to students. These include: 1) Replacement, 2) Serial Elimination, 3) Space-Split/Chunking, 4) Exhaustive Search, 5) Topographic/Tracing, 6) Discrepancy Detection, 7) Gaining Domain Knowledge from external sources, and 8) Pattern-Matching [7], [12], [15]. Incorporating more theory into the design of class troubleshooting interventions may help ensure that students go through all stages of the troubleshooting process when engaging with these exercises, and could even reveal steps which they need to improve at to become more adept troubleshooters, which is valuable for informing formative feedback. These recommendations are discipline-agnostic as well and so would be implementable in troubleshooting instruction across all engineering domains and contexts.

Lastly, future studies and instructional interventions should utilize more holistic methods for assessing students' troubleshooting skills – not just whether they could solve the problem or not, the number of faults corrected, or the time it took them to do so [5], [31], [33], [34], [35], [36], [37], [38], [39]. While those *performance* metrics are convenient, easily quantifiable, scalable, and somewhat indicative of troubleshooting proficiency, they do not provide any insight into students' troubleshooting processes. They reveal no meaningful information about the difficulties students encounter while troubleshooting, nor do they acknowledge any stages of the troubleshooting process they are successful with, despite ultimately failing to solve the problem. More detailed and comprehensive assessment methods are necessary for informing and providing formative feedback to students to help them improve their troubleshooting abilities. Two qualitative methods for data collection and instructional assessment that could remedy this issue, and which have shown promise in a few troubleshooting studies, are using a think-aloud protocol [4], [30], [40], [41] and recording the hypotheses that students make over the course of working on a troubleshooting problem [6], [10], [42], [43]. Collecting this information from students would likely allow facilitators and researchers to gain more nuanced insight into their troubleshooting processes, which would then allow them to address students' deficiencies more constructively. These assessment methods are discipline-agnostic as well and so would be implementable in troubleshooting instruction across all engineering domains and contexts.

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