



Examining Children’s Engineering Practices During an Engineering Activity in a Designed Learning Setting: A Focus on Troubleshooting (Fundamental)

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Abstract

Children spend most of their time in out-of-school settings. As a result, informal learning settings can play a significant role in children’s learning development. Museums and science centers are informal settings that are intentionally designed to promote learning and interest development. Studies show that these settings are where children begin to develop competencies, skills, knowledge and problem-solving processes that support participation in STEM-related careers. For example, many engineering exhibits have been designed for children to promote their engineering skills and practices as well as their understanding of engineering careers. One engineering practice is troubleshooting; troubleshooting is a practice used in many aspects of engineering work, including design, analysis, and programming. We situate this study in the engineering design literature as the task that our participants engaged in was an engineering design task. In this study, we examined ways young women engaged in design-based troubleshooting and compared them with what previous studies showed about the ways informed and beginning engineers troubleshoot their designs. To do so, we asked 7-11 years old girls with their caregivers to design a pneumatic ball run using pneumatic pistons in thirty minutes. The video data of four cases were then analyzed. Design-based troubleshooting was observed very often due to the immediate feedback they received (i.e., falling the ball means a problem). Our findings suggest that children can engage in some aspects of troubleshooting the same way as informed designers.

Introduction

Numerous reasons have fueled recent increased attention to pre-college engineering education, including an interest in increased technological and engineering literacy for all children; concern for increasing enrollment in engineering programs at universities [1]; an interest in increasing diversity within engineering; and a concern for social justice and equitable access to participation engineering. Numerous nationwide reports commissioned by the federal government have called for increased development in student enrollment in STEM fields to improve competitiveness on a global scale [2]. As groups are concerned with increasing the number of students pursuing engineering degrees and the diversity of the students pursuing engineering, researchers have recognized that this hinges on efforts that increase students' STEM knowledge and awareness of STEM fields [3]. However, present metrics seem to display only slow movement to validate positive demographic changes in engineering disciplines or show slowing in the decline of engineering associated career interests in student groups. Exposing children at a young age to necessary and relevant skills like engineering is imperative for addressing all the motivations for pre-college engineering education. As previous research has shown, children's early STEM experiences lay a foundation for the development of their STEM abilities as well as their interests in STEM dramatically impact their STEM learning throughout their educational experiences.

Exposing Children to Engineering Learning

In response to the need to expose children to engineering, engineering learning experiences are increasingly being developed in both in-school and out-of-school settings. In-school engineering learning experiences include the adoption of state curriculum standards which have included engineering, leading up to the creation of the national Next Generation Science Standards.

Meanwhile, various institutions and organizations have created engineering curricula for use in schools. Example curricula include the Engineering is Elementary curriculum that integrates engineering with science, the PictureSTEM curriculum which integrates science, technology, engineering, mathematics and literacy for K-2 classes [4], Novel Engineering, EPICS High [5], and Engineer Your World [6].

However, at the same time, children spend most of their time in out-of-school settings [9]. As a result, informal learning settings can play a significant role in children's learning development.

Students may learn about engineering during summer and afterschool programs as well as at home when reading books, playing with toys and games, and visiting museum exhibits.

Museums and science centers are informal settings that are intentionally designed to promote learning and interest development [35]. Studies show that these settings are where children begin to develop competencies, skills, knowledge and problem-solving processes that support participation in STEM-related careers [30; 36]. For example, many engineering exhibits have been designed for children to promote their engineering skills and practices as well as their understanding of engineering careers [30]. Participants' interaction with each other and exhibits can direct their learning and understanding of the presented topics [32].

Meanwhile, women have been historically underrepresented in engineering. By the time young women get to middle school their interest towards STEM is at its peak, [33] and their perceptions towards their future career have been shaped [34]. Thus, in this study, we specifically focus on 7-11 years old girls who visited a museum and interacted with an engineering exhibit with other family members. We first investigate how the girls engage in design-based troubleshooting, and then we look at their similarities and differences with informed designers.

Engineering Design: Troubleshooting

The Framework for K-12 Science Education [12] introduces engineering practices along with scientific inquiry appropriate to be used for a K-12 student. One of the engineering design practices that separate engineering design and science is troubleshooting [13]. Troubleshooting is an essential component for successful practicing engineers. When creating any product or system, engineers continuously engage in troubleshooting. Troubleshooting, in general, is a problem-solving ability and thinking process that can be attributed and applied to operators, equipment, process and any engineering systems [14]. However, design-based troubleshooting refers to strategies to diagnose and fix the problematic parts of the designed system, and then to undergo iterations to re-design the parts or the whole system [15]. In other words, design-based troubleshooting is a practice that allows engineers to reach an optimum solution by identifying problems, developing suitable solutions and improving them. While this practice is fundamental to design process, many designers, especially the inexperienced ones, either skip this practice or do not pay careful attention when conducting it. The unfocused troubleshooting has been highlighted by Crismond and Adams in their Informed Design Matrix [16]. They have stated that beginning designers use an unfocused approach o troubleshooting when testing a system/prototype, whereas informed designers pay focused attention on crucial problem areas during troubleshooting.

Many undergraduate-level studies focused on engineering students' troubleshooting skills. They have focused on students' design-based troubleshooting experiences in various engineering areas such biomedical engineering [17]. Many studies also introduced techniques and strategies to teach and develop design-based troubleshooting in engineering students. For example, in

chemical engineering, Gurmen and colleagues [18] discussed an interactive computer module for MicroPlant that encourage and promote students to troubleshoot. In a different study, Liang [19] has discussed a web-based learning framework that engages engineering students in troubleshooting in automotive braking systems.

While design-based troubleshooting is an essential practice in engineering design, it has been understudied in K-12 engineering education [15]. Not many studies have focused on K-12 student's design-based troubleshooting skills. Insufficient preparation of K-12 students for troubleshooting can be a significant barrier to engaging in engineering design projects and realizing the technology's potential in these projects [20]. To prepare K-12 students to do focused and diagnostic troubleshooting, studies have focused on developing teacher pedagogical content knowledge [21], [22] and appropriate engineering courses to engage students in design-based troubleshooting [27] [22]. However, none of these studies included rigorous information how students engage in design-based troubleshooting. While training teachers essential to prepare K-12 students better, investigating how students practice troubleshooting during engineering design is necessary.

Theoretical Framework

To investigate the ways children engage in troubleshooting, we used the Informed Design Teaching and Learning Matrix by Crismond and Adams [16]. This matrix is developed as a representation of a teacher's pedagogical content knowledge in engineering design. The matrix displays 11 patterns of design behavior that describes and focuses on the ways both informed and beginning designers think and behave. This matrix is a prescriptive tool that teachers can use when teaching engineering design and while observing students' behaviors during engineering

design. While alternative models exist for engineering design and more specifically troubleshooting [23], we used this model as it covers the age of target group of this study.

Pattern G of this matrix describes design-based troubleshooting which includes examples of behaviors that both informed designers and beginning designers may enact. This pattern suggests that informed designers engage in four consecutive actions when doing troubleshooting. These actions include: (1) Observing: carefully observing the performance of the prototype when testing it teaching four actions to happen in a consecutive order, (2) Diagnosing: detecting the problem, (3) Explaining; explaining possible reasons that the problem occurs, and (4) Fixing: suggesting remedies to fix the problem. In this study, we carefully explored if children took these actions when doing troubleshooting during the engineering design task and if they took, in what order.

Purpose of the Study

This project was a partnership between the Science Museum, and a University Research Institute. The overarching purpose of this project was to explore engineering experiences of girls when engaging in engineering activities in an informal learning setting, and how parents facilitate their girls' engagement in engineering. Given the lack of K-12 engineering education towards understanding how children engage in troubleshooting during engineering design experiences, we recognize the importance of characterizing children's design-based troubleshooting. Therefore, in this study, we focus on design-based troubleshooting, and we investigate the research questions below:

- 1) How do 7-11 years old children engage in troubleshooting during an engineering design activity?
- 2) How is their engagement different or similar than informed designers?

Methods

A multiple case study approach was used to explore girls' engineering experiences within a real-life context with the focus on design-based troubleshooting. Within one engineering exhibit at the Science Museum, we invited families who have girls aged 7-11 to participate in this study. They were asked to create a ball run using a series of magnetic frames with piston assemblies, hinged ramps. The goal was to design a ramp system that would ensure that the ball successfully traveled from start to finish where the end position was higher than the start position (see the Figure 1).

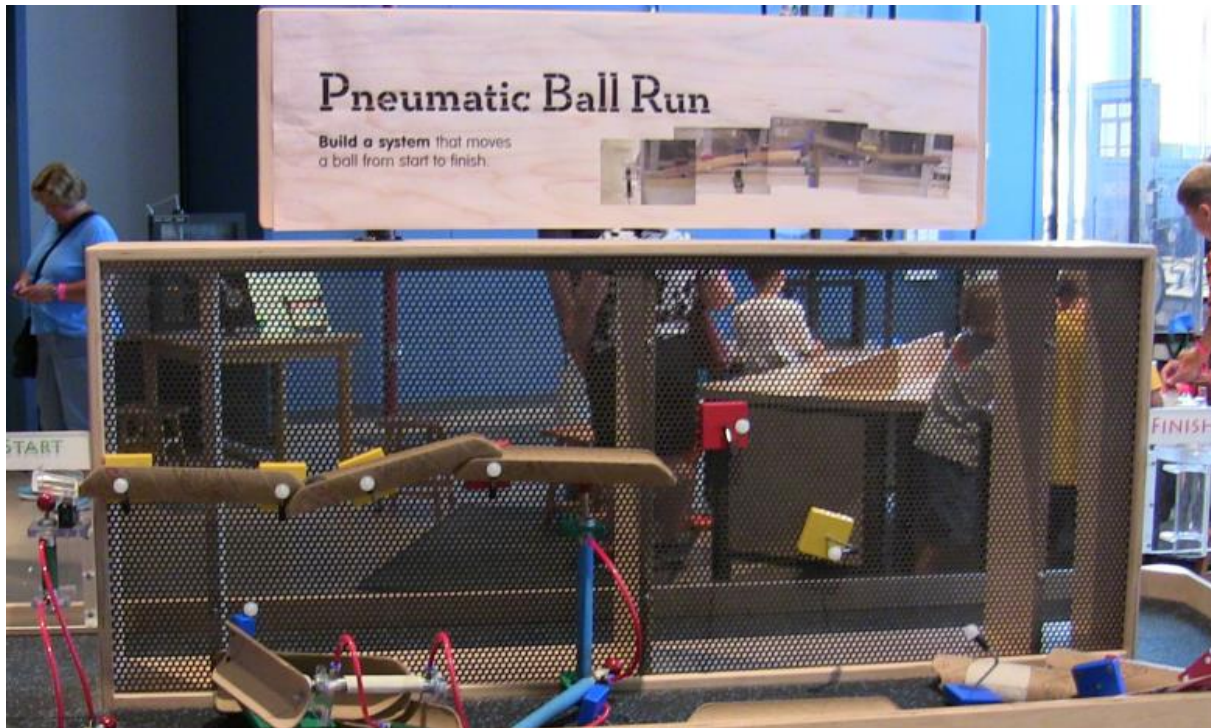


Figure 1. Pneumatic Ball Run

Multiple Case Studies

The multiple case study research was used in this study as a research methodology because it would allow us to investigate the in-depth experiences of girls who engaged in an engineering

design activity. Multiple case study research is an excellent tool for learning phenomena in a real-life setting and is powerful when used in an exploratory manner [26]. Multiple cases have the potential to allow comprehensive examination as it permits for analysis to compare situations, and identify convergence and divergence [24]. In our research, multiple cases were used in both action and narrative ways to uncover how the girls engage in design-based troubleshooting. In action, we focused on what they do during the engineering design activity. The narrative way helped us uncover additional information for the actual words of the family members. Case study research can be generalizable even if only one or a few cases are being used [28]. To add to the applicability of the cases should be selected according to how well they represent the phenomenon under consideration [25] which is design-based troubleshooting in this study.

Data Sources

In this study, we selected four cases of children of 7-11 years old who came to the museum with their families. The cases were purposefully selected given their similarities and differences to provide us a broader picture of how children engage in troubleshooting. In all the cases, the activity was led by the child and extensive work was done. However, two cases were successfully able to build the ramp, but the other two were not able to solve the problem. The data source used in this study include video recordings collected while families engaged in this exhibit. All the cases consisted of a daughter and a parent (either mother or father), but in one case a male sibling participated with his sister and mother. A brief description of the cases is illustrated in Table 1.

Table 1. Description of Cases

Case	Case participants	Case Characteristics	Achieved the Goal
Case #1	Father & Daughter	Child-led & Extensive work	Yes
Case #2	Mother & Daughter	Child-led & Extensive work	Yes
Case #3	Mother & Daughter	Child-led & Extensive work	No
Case #4	Mother, Daughter, and Son	Child-led & Extensive work	No

Data Analysis

To analyze the data, we initially developed a codebook using pattern G in the matrix developed by Crismond and Adams [16]. The codebook first included the actions and definitions. Then, two authors watched one video and discussed the instances of actions they observed. Based on that conversation, the actions became clearer, and examples were added to codebook (See Appendix 1).

After we reached an inter-rater agreement, we divided the videos among the researchers. To do the analysis, we followed the seven non-linear phases that [13] introduced. The phases in this model include: (1) viewing attentively the video data, (2) describing the video data, (3) identifying critical events, (4) transcribing, (5) coding, (6) constructing a storyline, and (7) composing a narrative. Each researcher analyzed one or two videos individually, but the findings were discussed with the research team.

Findings

After analyzing videos of all four cases, we noticed that all the children engaged in design-based troubleshooting very often. The actions included Observing and Fixing which happened many times, and Diagnosing and Explaining.

While the focus of this study was not parents' support, we have noticed that parents have an impact on their children's engagement in design-based troubleshooting. In all the four cases, children led the activity. However, we have seen many examples of design-based troubleshooting happening because of the parents' support. Parents supported their children in doing all the four actions of troubleshooting during this activity. However, they were more involved in Fixing as they would suggest different ways to solve the problem that has occurred during the test.

Design-Based Troubleshooting Actions

Observing

Children observed the performance of their prototype. Observing in troubleshooting happens at the same time as testing the prototype. Children would test the entire or segments of the prototype (i.e., the ramp they designed) in two ways: (1) by observing the ball running on the ramp, and (2) by testing the tools they used in building the ramp. While observing, children and adult would discuss what went wrong or did not; they were both involved in finding the problem.

Informed Designer vs. Beginning Designers. We have seen children acting both as informed designers and beginning designers on different occasions when observing their prototype performance. According to Crismond and Adams, informed designers tend to focus on the parts that may not be working well [16]. Informed designers actively look for critical events and patterns that cause the system to fail. In contrast, beginning designers would miss what happens during testing and tend to be unfocused in realizing what went wrong. We have observed many instances of children being focused on observing the performance of their prototype to see

where the problem area is. Sometimes children would repeat the test several times to make sure they found the problem. Some other times, they divided the work of observing to pay focused attention to each part. One child asked her father to pay attention to the half of ramp, while she is watching the second half and running the ball: “Look at this part, and I’ll here to here [pointing to some segments]. See where if the ball falls.”. On the other hand, we have seen examples of unfocused testing which resulted in not being able to detect the problem.

Diagnosing

Diagnosing happened in several ways including naming the detected problem, using non-verbal cues to show the problematic areas, or using verbal cues to demonstrate the problematic areas. When naming the problem, children would say exactly what went wrong. For example, one child detected the problem by saying, “That one was too slow, gush.” Some children would use non-verbal cues like pointing to the problematic areas or re-testing the segment that the problem was detected either with or without using the ball. This could follow by a verbal explanation of the problem. Like one child after pointing to the problematic area said, “Okay mom. That one moves not hard enough at all.” Finally, some children would just mention that they have detected the problem. For example, we observed instances that children said, “oh, I know what the problem is,” and then she started trying out other ideas or fixing the problem.

Informed Designer vs. Beginning Designers. When detecting a problem, we observed children acting like informed designers on different occasions. Instances were observed that children realized the problem by recognizing the similarities of the problem to the previous problems even without testing it. For example, after a child built a ramp, she looked at it and said aloud, “No, it’s gonna flip now.” When the adult asked to test it, she responded, “No, let’s remove this. It’s like the other one didn’t work. Remember, right?” However, in some cases even when

problems were similar to the ones happened before, like using the pneumatic piston in a wrong direction or using a wrong slop for the ramps, children did not recognize the similarities and did not notice the problem.

Explaining

Children mostly provided explanations of the cause of the problem with either referring to the problem or providing a remedy. This means that children usually provided a cause-effect explanation of why a problem happened through talking about the detected problem, or by providing suggestions to fix the problem. They also sometimes explained the cause during the testing and observing phase. An example of explaining the cause by talking about the problem includes a child saying, “That one went a little too far. Oooh. Cuz, it has a lot of flip to it.”

Another child, mentioned the cause of the problem by providing a remedy, “Oh, I want so hard to went backwards. I need to ... not hit so hard, but hard enough”. She is providing the cause that she has thrown the ball too hard but suggesting a way to fix it by saying they need to throw it less hard than how they tried.

Informed Designer vs. Beginning Designers. According to Crismond and Adams, to find the cause of a problem, informed designers use functional knowledge to look at how a system and subsystems work and interact with each other [16]. In other words, they zoom their attention in, look at the performance of the components of the prototype, and then zoom out, look at the prototype performance as a whole system. Such focusing of attention helps designers to explain the cause of the problem. Informed designers also find the cause of a problem using casual reasoning by recognizing the patterns of exceptional system performance in different rounds of testing. In this study, across all four cases, we did not encounter many instances that children

behaved like informed designers when providing possible cause-effect explanations of the cause of a problem.

Fixing

Fixing was listed as the last action to be taught in Crismond and Adams' matrix [16]. It involves proposing ways to remedy and fix the detected problem. In this engineering task, Fixing was the last step before re-testing the system. Given the nature of the task, participants received immediate feedback (i.e., falling off the ball) that a flaw exists in the design of the prototype. Therefore, they became involved in fixing the problem very often. Fixing occurred in different ways. First, children and adults would brainstorm and generate ideas. This could include evaluating the ideas and employing the best idea. They would debate why they think one idea would work or would perform better than other ideas. To do that, they used patterns they have observed previously (informed designing; more information provided below). Below is the conversation between a daughter and a mother, after testing their prototype and facing a problem. They brainstormed some ideas and evaluated the ideas based on the patterns they see.

“Child: Wait, we have to move it closer then?”

Mother: We could do this. Cuz we actually want it up higher. Right? So, what if we cansome way holding this... oh, I don't know.

[manipulating with the tools]

Child: Wait, it's we.. push it. It should go to about here. Oh, should we use that and have it go up a long one like this. So, it can go up.... Like this one went? Yeah, Mama, you're right.”

Mother: Okay, wait. Let's see what happens when we do this. [fix and test]"

However, in one case which included a daughter and a father, only the daughter's ideas were implemented and tested without evaluating the idea or considering the father's ideas. Also, some instances happened that children would jump into fixing without explaining their ideas. In these instances, we did not notice any clues of if children had an idea in mind or they were just trying to find a way to fix the problem unless adults asked them what they were doing.

Similar to Crismond and Adams' description of Fixing [16], Fixing in this task involved simple fixing, adding additional features or designing an entirely new system. Instances were observed that children knocked down what they designed and designed an entirely new system. We have also seen examples of detected flaws inspiring new ideas for simple fixes, like moving a piston higher or placing a ramp at a different angle or adding hinges to the initial design.

Informed Designer vs. Beginning Designers. Not all the children engaged in Fixing the same as informed designers do. Crismond and Adams [16] stated that informed designers use case-based reasoning and recognize the patterns that cause faulty performance of the system based on similar cases they faced before. Then, they use the casual reasoning to propose ideas to fix the system. In these four cases, some instances were observed that children were able to see patterns and refer to their previous experiences to justify why an idea would or would not work (an example is previously provided). However, we have encountered many children employing the same faulty ideas as they used before to solve similar problems.

Sequences of Actions

Crismond and Adams suggested teachers teach design-based troubleshooting actions in the following order: Observing, Diagnosing, Explaining and Fixing [16]. Although drawing a clear

boundary between each of this action is necessary when teaching them to students, the boundary between these actions was not always clear when enacted by children in this task. In many instances, actions were embedded in each other in which distinguishing between them was difficult. Diagnosing and Explaining were embedded in each other in several examples. Diagnosing a problem happened while (or a bit after) observing the performance of the prototype most of the times. Fixing and Explaining were also embedded in each other in many instances meaning that explanation of the cause and remedy occurred at the same time.

While the boundaries between the actions were not always clear, we noticed patterns of the ways children engage in the actions of design-based troubleshooting. We observed patterns of different orders of actions that children engaged in design-based troubleshooting. The most frequent one was, “Observing-Diagnosing-Fixing.” We also observed “Observing-Fixing-Observing-Fixing” in which children did not discuss what the problem and the cause are and jumped into fixing after testing. In these instances, fixing included either redesigning or adding additional components to the design. Although not as frequent as the sequences mentioned before, we observed examples of “Observing-Diagnosing-Explaining-Fixing” and “Observing-Diagnosing & Explaining-Fixing.” This suggests that within the more unstructured engineering learning environments outside of the formal classroom, the order of troubleshooting actions may not tend to follow a fixed or predictable pattern such as the one described by Crismond and Adams [16].

Discussion

In this study, we focused on girls’ engagement in design-based troubleshooting by analyzing four cases of girls and their family members engaging in an engineering design task. To investigate design-based troubleshooting, we utilized the pattern G of the Informed Design

Teaching and Learning Matrix [16] in which describes four actions for teaching design-based troubleshooting. These four actions include Observing, Diagnosing, Explaining, and Fixing. We intended to explore if girls act like informed designers or beginning designers when doing design-based troubleshooting. We also investigated in what order girls engage in these actions.

Through our analysis, we observed girls engaged in all four actions of design-based troubleshooting. We have observed many examples that girls enacted like informed designers when observing the performance of their prototype and diagnosing the problem. Although not a lot, in some instances the girls used case-based reasoning after suggesting remedies for fixing the detected problem which is what informed designers tend to do. However, they did not provide explanations of why a problem happened very often, and the explanations being discussed were not always detailed and precise and were not reasoned based on patterns previously recognized. One reason for this might be that they did not need to explain the cause of the problem to solve that problem. We have noticed patterns of the different orders that the actions occurred. However, we realized that drawing a clear boundary between the actions was not always easy and the actions happened embedded in each other.

Conclusion & Implications

Overall, this study provides evidence that girls have the potential to engage in design-based troubleshooting actions when working on engineering design tasks. However, this engagement does not always happen in the order that is suggested by Crismond and Adams [16] to be taught to them. Moreover, depending on the situation, girls may engage in design-based troubleshooting the same as informed designers. However, they may perform like beginning designers when they need to recognize patterns and do case-based reasoning like explaining a cause and suggesting a remedy. One way to help young women to perform like informed

designers is to provide enough support and scaffolding while they engage in engineering design. Therefore, further research is needed to investigate the role of parental engagement in their girls' troubleshooting and design skills, and the type and amount of support girls need to perform like informed designers.

This study has provided rich insights into troubleshooting experiences of the four girls engaging in engineering design tasks with their family members. We have seen patterns of the girls engaging in all the four design-based troubleshooting actions in some degrees. Since our findings provide evidence of children's ability to troubleshoot, this study lays a foundation for future research to investigate troubleshooting in all children. Further research is needed to investigate how common these patterns can be observed as practiced by children. In addition, conducting the same study with boys would help researchers to make a broader conclusion about children's troubleshooting abilities.

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Appendix

Table A.1. Design-based Troubleshooting Actions

Design-Based Troubleshooting				
Action	Observing	Diagnosing	Explaining	Fixing
Definition	Observation of the overall performance of the prototype during prototype testing to detect any unexpected or out of range behaviors.	Actual diagnosis of the problem, where the designer notices a problem in the product's performance.	Possible cause-effect explanation of why certain behaviors (problem) occur.	Involves proposing new ways to remedy and fix the design or prototype.
Findings	Includes looking at the performance of the prototype <ul style="list-style-type: none"> • the prototype as a whole system • parts of the prototype as sub-system 	Includes <ul style="list-style-type: none"> • naming the problem • using nonverbal cues/actions to show the problematic area • using verbal cues that demonstrates detecting of problem 	Includes <ul style="list-style-type: none"> • providing explanations of why the problem happened 	Includes <ul style="list-style-type: none"> • Less analytical, just one person suggesting ideas and applying those ideas. • Brainstorming and generating ideas as a group This can include evaluating the ideas or not. • Fixing the problematic areas without providing explanations

				<ul style="list-style-type: none">• Explaining why a suggestion may work and discussing that in the group
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