How an Undergraduate Group of Design Students Solved Wiring Errors during the Prototyping of an Interactive Artifact

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ABSTRACT

The introduction of maker technology and personal fabrication has radically changed how we learn, design, and innovate. In recent years, a growing number of people have begun using a broad range of creative technologies. A common challenge with using these technologies is the difficulties during electronic circuit prototyping, particularly for end-users. This research investigates the causes of wiring problems and the troubleshooting strategies used during the prototyping of electronic circuits by nonexpert users. We conducted an ethnographic study of students at a university design school engaged in prototyping electronic circuits with creative technologies. We performed a microanalysis of the students' interactions and dialogues according to the distributed cognition framework. Results show the significance of having meaningful information on the prototyping tool in addition to the importance of the students sharing common ground so that they can effectively detect and solve wiring errors. Our conclusions highlight some relations between types of wiring errors and solution strategies.

CCS CONCEPTS

• **Social and professional topics**;; • **Human-centered computing**;;

KEYWORDS

Circuits Wiring, Breadboard, Distributed Cognition, Design, Education

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1 INTRODUCTION

The introduction of personal fabrication has radically modified how we learn, design, and innovate [1, 4, 9]. In recent years, this movement, also called the maker movement, has involved a growing number of people not skilled with digital technologies [3]. The rise in nonexpert users, parallel to the growing availability of complex digital creative technologies, has increased the critical aspects of using these technologies. Some studies in human-computer interaction have partially explored the problematics of using creative technologies [2, 18]. In particular, according to recent research, most issues using these technologies concern the errors caused during the wiring of electronic circuits [5, 6]. Consequently, in the last few years, research has focused on the breadboard's redesign, with the aim of providing a better experience and support to the users engaged in prototyping and debugging electronic circuits [6]. Studies in education have explored the errors in e-textile circuit construction, such as current flow, missing connections, and component polarity [15]. More recently, another study introducing a microcontroller in e-textile circuits added challenges such as the wrong microcontroller pin and coding-related errors [13]. While these previous studies gave significant contributions to research into the prototyping of electronic circuits, today little information exists that clarifies the factors that favor errors by nonexpert users during the wiring of electronic circuits. An understanding of these factors remains a challenge that creates the need for further investigations [6]. The research questions this study aims to answer are: 1) What types of common errors emerge during wiring? 2) Why do wiring errors happen during the prototyping of electronic circuits? 3) How are these wiring errors detected and solved? This research explores and analyzes the factors that cause errors and the troubleshooting strategies by nonexpert users during electronic circuit prototyping. To this end, we conducted an ethnographic study of undergraduate students engaged in the prototyping of interactive digital artifacts, performing a microanalysis of the interactions and the dialogues of teams of design students during the prototyping activity, according to the distributed cognition framework [10]. This study highlights the factors that sustain or hinder cognitive processes when nonexpert users prototype electronic circuits on a breadboard. Our research highlights the relations between the circuit construction errors and the distributed context composed of teammates, knowledge, and artifacts that contribute to error detection and problem-solving strategies. Our contribution highlights the need to redesign the electronic prototyping tools to better support distributed processes between people, artifacts, and representations in circuit-wiring problem-solving tasks.

2 RELATED WORKS

According to research conducted with subjects with different experiences, wiring errors are frequent during the construction of electronic circuits. Subjects wiring an electronic circuit on a breadboard have a high number of problems and only a tiny percentage of participants completed the circuit correctly [5]. Those errors cannot be solved easily and obstruct the completion of the circuit [7, 16]. However, these studies show the difficulties in constructing

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electronic circuits on the breadboards; they do not specify how and why wiring errors occurred.

Recent studies have reported microcontroller pin errors in e-textile and breadboard circuits [5, 7, 13, 14]. Identifying a pin on the microcontroller by counting is prone to errors, while identifying the pins relying on the numbers depicted on the micro reduces the errors [7]. Studies with students report the critical relation between program and circuit [5, 8]. According to other studies conducted with students, programming skills can be improved by mapping the code with the electronic circuit depicted on a sheet of paper [12, 13]. A recent study shows that nearly one-third of debugging is dedicated to the circuit [11]. Similarly, a study conducted on students and teachers shows that frequent use of different debugging strategies reduces the number of errors [12]. Studies conducted with e-textiles show that students significantly improved their ability to create a closed circuit and reduced the number of missing connections as well as component polarity problems [8, 13, 15]. Studies show that creating the circuit layout in e-textiles is complex; in particular, transferring the diagram on paper into a physical circuit is subject to spatial and wiring errors [11, 17]. Redesigning the circuit diagram plays a crucial role in coordinating group understanding and enactment [12]. The blueprint and intermediate representations support the creation of the circuit layout as a design scaffold [14]. This work contributes to building on this knowledge by presenting the role of information on the breadboard-wiring activities of teams of undergraduate students.

To date, there are no investigations that thoroughly clarify the role of information representations in making errors during the wiring of an electronic circuit through the support of the breadboard by team members. Moreover, it is unclear what external representations support this collaboration and what types of errors benefit from it. Our study presents a microanalysis of a unit of analysis of the wiring activities of circuits by a group of students in a design course to clarify the reasons for the wiring errors and their solutions. This study explains circuit troubleshooting strategies, informs the design of new systems that make the most of these dynamics, and provides insights for educators and instructors.

3 METHOD

We conducted an ethnographic study of a third-year design bachelor course at the University of Dundee. The participated observations were conducted for the whole duration of the course, over a period of 12 weeks.

3.1 Study Subjects

The interaction design courses at the University of Dundee had the objective of providing the students with a comprehensive and direct experience with the design and prototyping of interactive digital artifacts. The course was held twice a week for a duration of 12 weeks. The class was composed of 51 students, and it had 26 product designers (PDs), 19 interaction designers (IxDs), and six master students in product design. The majority of them had already had, in the second year, the shared courses in physical computing and data visualization.

The design brief challenged the students to design audible interactive artifacts for domestic environments that would provide information from the web through the audio channel. Seventeen groups, composed of two PDs and one IxD, were created based on the students' interests. All the students were invited to participate in our study, and 21 agreed to participate. The age of the participants ranged from 20 to 27; nine were female, and 12 were male. We chose to observe one group, composed of three students (males): their ages ranged from 20 to 22. This group was chosen because all of its members agreed to participate in the study.

3.2 The Task

The specific activity in the fifth week of the course was the creation of an early prototype capable of generating tones through a speaker connected to a microcontroller. The Arduino Micro, mainly used in this study, is a small microcontroller capable of performing simple digital operations. The Micro has 20 digital input/output pins marked by numbers, of which seven, marked by (~), can be used as analog outputs to connect an analog actuator like a speaker. An integrated development environment (IDE) can program the Micro via a USB cable connected to a computer. The Micro requires the use of a breadboard, which has a matrix of similar holes and alphanumerical characters and signs.

3.3 Apparatus

The course technician, provided a set of electronic components (microcontroller, speakers, pushbuttons, resistors) and a copy of the microcontroller pin diagram to each team. The Micro discussed in this article was programmed by the interaction design students using the Arduino IDE, already installed on their computers. The jumper wires necessary to wire the circuit were created by students by cutting parts from black and red reed wires. For the study, we used three fixed cameras and one mobile camera.

3.4 Data Gathering and Analysis

We conducted fieldwork observations, interviews, and prototypes analyses. A researcher supported by one graduate student assisted with classroom observations and data collection. Subsequent to observation, interviews were also conducted at the studio at the end of each day. All the field observations were video recorded and conducted in the third-year design studio. In addition to video and audio from the observations and interviews, photos, documents, and field notes were collected. Sixteen days of fieldwork observation were conducted, yielding a total of 94 hours of video footage.

Our analysis began with a review of data by indexing and highlighting sessions. After a first preliminary review of the video, 37.5 hours of video were selected. Then, all the videos in which students were performing activities related to the wiring of the electronic circuits were selected for further analysis for a total of 4.5 hours of video. Particular interest was given to video of the initial phases of the wiring activities of the circuits, in particular when wrong wiring occurred. The dialogues of those selected videos were transcribed by the researchers, together with all the students' actions (line of sight, pointing, head positions) and representations of the states of the electronic circuits. Excerpts of the videos were selected, and a detailed analysis of the data was conducted through the distributed cognition theoretical framework [10]. Two researchers coded and mapped data to understand how, where, and why errors occurred and how those errors were solved.

4 RESULTS

We report group's activities at a stage where the circuit was partially assembled on the half-size breadboard, with the microcontroller and the black and red wires for powering the breadboard already inserted. We describe here the microanalysis of a representative excerpt of the wiring of the speaker to the circuit. The team decided to use a division of labor based on a collaborative strategy. F1 wired the circuit; F2 supervised F1; F3 assisted F1.

First, F1 asked, "[Is] this thingy nine?" to confirm the number of the Micro pin. The information about the pin (9) of the Micro was stored in the student's short-term memory, verbally communicated earlier by F2 to F1. Simultaneously, F1 pointed with the speaker's black wire to the area close to pin 9 of the Micro while the other students observed the circuit. F1 asked again, "Is it nine on the breadboard or nine on this?" F1 pointed at the number 9 of the breadboard with the black wire, while pronouncing the first "nine." Then he quickly moved the wire at pin 9, saying the second "nine." With F1's questions and actions on the circuit, the student requested the attention of the team. All the students looked at F1's actions, suggesting that they listened to the questions and understood the need to pay attention. Through this collective focalization of attention, the students created a context to collaborate and develop a shared understanding of the problem. To correct the polarity error wiring, F2 took the black speaker wire from F1's hand, pointed to the blue line printed on the breadboard rails, and said, "That should go to the ground, with the black." With that information in short-term memory, F1 quickly replaced the grey wire inserted into the ground rail with the black wire.

In the activity to connect the second wire to the microcontroller pin 9, F1 started counting from pin 12 and slowly moved the wire from one pin to another while he was counting aloud (Figure 1, left). Reaching the head of pin 9, F1 slowly moved the wire toward the corresponding row of the breadboard. Counting apparently served as a guide for the student while also articulating his cognitive processes for the others. The information on the Micro and the breadboard appeared to guide F1, who did not have a clear strategy. At this stage, it seemed that the availability of information in the environment guided the organization of the students' actions and that F1 was behaving opportunistically. F1 wrongly inserted the wire into row 5 half a minute after having identified pin head 9 (on row 4) by counting. Because the circuit was powered, the students were expecting a sound from the speaker, which instead remained silent (Figure 1, middle). F1 guessed that the problem was the wire being on the wrong row of the breadboard. The student was frustrated, and the other members observed silently. F1 rotated the breadboard to see the wiring connections better and decided to count the microcontroller pins with the help of a pen. F1 positioned the bottom of the pen parallel to the Micro rows and started counting aloud from pin 12 toward pin 9, slowly moving the pen, row by row for each counting utterance (Figure 1, right). Once he arrived at row 3 of the breadboard, connected with pin 10 of the Micro, he paused and removed the pen. F1 quickly removed the grey wire from row 5 and inserted it in row 4. For a moment the speaker emitted a tone that continued after the insertion of the wire was concluded. In this space, the pen acted as a coordination medium between rows, Micro pins, and the counting activity, transforming it into a combinatory artifact for computation between heterogeneous information representation systems.

We could say that the group's circuit wiring was situated because the course of actions and the organization of how they were carried out were mutually constraining. All the team members listened and observed the actions that F1 performed on the circuit; if F2 had not had access to that information, the polarity error would probably not have been detected by F2 and corrected by F1. These examples show that all the students had similar mental models about how the breadboard and microcontroller work because they received the same education and training. This shared background and knowledge were the basis of their coordination. The structure of the tasks and the actions of each student were available to the group, and they could consequently benefit from error detection. This had implications not only for the discovery and detection of errors but also for learning. Moreover, distributed access to information supported redundant information storage among the participants, needed to detect and correct errors. These strategies reveal that a fundamental property of distributed cognitive systems is that they permit the exploration of more alternatives than a single person can carry out.

5 DISCUSSION

This research proposes a definition and analysis of the factors that cause errors, and the solutions to those errors, during the wiring of electronic circuits. We conducted an ethnographic study of undergraduate students involved in the prototyping of electronic circuits, performing a microanalysis of data according to the distributed cognition framework. The study highlighted the factors that supported or impeded the students in the wiring of electronic circuits.

Our study highlights the pin-row alignments and the polarity of the components as the most frequent type of errors. In the case of the pin-row alignment errors, external artifacts and contextual information helped the students recognize and solve the wiring problems. To identify the breadboard row corresponding to a determined Micro pin, the students used three levels of information. The first level was the information printed on the Micro board. That information was ambiguous because it could not support the student in identifying the correct pin. This ambiguity was solved by counting, which strategy was itself prone to further errors. The second level of information was on the Micro pin legs, which connect with the breadboard. Once the students identified the right pin head by counting, they moved this information to the Micro pin legs on the sides. To accomplish this operation, the students aligned the pin head to its leg by a visual projection. This operation is subject to misalignment error, because all the legs were similar and there was no information for distinguishing them. On the third level, the information on the breadboard was constituted of undistinguished chunks of similarly aligned rows of holes. Our data show how students regularly lost their reference point and thus inserted the wire on a wrong breadboard row. To detect and solve these errors, the student aligned these three levels of information using a pen.

This study highlights that if the students have reference information on the artifacts they construct, they can accurately perform

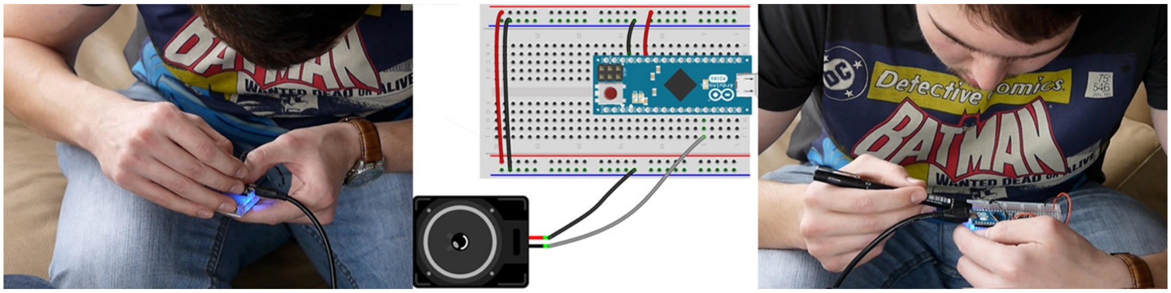

Figure 1: F1 counting micro pins with the grey wire (left). The grey wire on row 5 instead of row 4 (middle). F1 used the pen to count the pins and rows (right).

recognition, memorization, and computation instead of being driven by volatile, emergent, and opportunistic interactions. Our results align with other studies that highlighted miswiring problems on circuit wiring [5, 7]. Our work contributes to expanding this increasing knowledge by highlighting the lack of simple and contextual information during the wiring activities as one possible reason for these miswiring problems. Results show that this information might be essential for students who need to scaffold their learning processes. We could speculate that as more information becomes highly available and visible, it might also create more chances for teammates to contribute to resolving these types of errors. These results suggested that novel electronic prototyping tools should provide more meaningful information to support nonexpert students and experts.

According to our study, the common ground between students, supported by the distributed representations of information, played an essential role in detecting and solving wiring errors. Our data shows that component polarity errors are more efficiently solved by teammates' contributions than pin-row alignment errors. These results indicate that students having multiple access points to information distributed in their learning environments, combined with their common ground, has a fundamental role in solving wiring errors. For example, when F1 had difficulties wiring the ground pin, the coordination of teammates, supported by their common ground, enabled the student to identify the pin precisely. These results align with other studies highlighting teammates' roles in debugging the wiring of e-textile electronics [12, 14]. Our study contributes to this increasing body of knowledge by highlighting the role of shared knowledge and common ground in detecting and solving errors, and it proposes an initial exploration of the relation between types of wiring errors and troubleshooting strategies. These findings might be due to the fact that collaboration in complex activities is better adapted to the circumstances and may highlight errors better than noncollaborative activities do [10]. We might speculate that the wiring activities of nonexpert students with common ground should be accomplished in shared learning environments populated with wiring artifacts with highly visible and understandable information. These artifacts might be composed by users collaboratively. The artifacts students construct should provide highly visible and understandable information of their internal dynamics to the user and to the students present in the proximity of the learning environments. The students' learning should be organized by exploiting these shared distributed capabilities with the careful composition of team members and the setting up of appropriate learning environments.

5.1 Limitations

The simplicity of the tasks might have partially limited this study. This simplicity might have shown only generic problems, which are important for nonexpert students and users. Studying more complex circuit prototyping might have highlighted more complex problematics of circuit wiring. We are planning further research to study more expert users engaged in wiring more complex circuits and to highlight the differences between the studies.

6 CONCLUSION AND FURTHER STUDY

This research presented the results of an ethnographic study focused on exploring the problematics met by students during the wiring of electronic circuits on a breadboard. The study met our research objectives and suggested interesting lines of investigation regarding the challenges encountered by students during circuit wiring, in particular: how information supported or hindered the students' activities; how the situated approach can support circuit wiring; and how the sociotechnical context (the sharing of knowledge, common ground, activity visibility) plays an important role in the discovery and solutions of wiring problems. More studies of the dimensions discussed above are planned in the near future, as are the design of novel systems that explore features suggested in this study.

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