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Shifts in high school students' conceptions of sensor-based devices and toys

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Abstract: Advancing conceptions of computing system internals—structural composition and dynamic behavior— is key to learning computing and critically engaging with it. However, novices' informal ideas challenge their engagement. In this study, I conducted and qualitatively analyzed ten students' interviews about a pair of functionally similar computing artifacts before and after a 14-week-long online electronic textiles unit. The analysis revealed that, post-unit, students had developed advanced conceptions of computing systems, both structurally and behaviorally. They frequently accounted for computing and explained internal dynamics in terms of data and control flow. I discuss implications of the findings for future computing education research and designs to promote critical computing learning.

Keywords: Computing learning, student conceptions, physical computing, electronic textiles.

Introduction & Background

A primary objective of introductory computing education is to help learners develop a conception of layers of abstractions between software and hardware that make everyday computing systems functional (CSTA, 2017). With devices such as automatic soap dispensers and facial recognition software critiqued for biases against marginalized peoples (e.g., Costanza-Chock, 2020), understanding the internal dynamics of computing systems is important. But, we barely know how learners think about computing devices and their internal workings.

Student conceptions of physical computing artifacts consist of structure, behavior, and function (Bhatta & Goel, 1997). The physical parts of the system and interconnections make the structural composition; roles of different elements cover the functional aspects; and the underlying logic causing outcomes through control and data flows accounts for the behavior. For sensor-based devices: (1) the *structural* aspects include microcontrollers, sensors, lights, and the physical interconnections; (2) the *functional* aspects consist of lights as outputs and sensors as inputs; and (3) the *behavioral* aspects include the underlying program logic that causes outcomes.

In prior studies, learners have been interviewed about coffee makers, stoplights, and smartphones to capture their conceptions (e.g., Przybylla & Romieke, 2014). Across, novices' limited understanding about these systems stands out. With only input and output components visible, learners develop naïve notions about the inner structural composition of these systems. A few studies (Cederqvist, 2020; Jayathirtha & Kafai; 2021) have noted how even students within computing courses have a limited understanding of these computing devices. Concepts of control and data flow—how inputs such as touch and light intensity cause different outcomes—were almost inaccessible to novices (e.g., Cederqvist, 2020). In this paper, we conducted and qualitatively analyzed student interviews (Creswell & Poth, 2016) before and after an introductory e-textiles unit within a high school online class. We asked: How did student conceptions, particularly their structural and behavioral understanding, of physical computing systems shift at the end of the unit?

Methodology

Context and participants

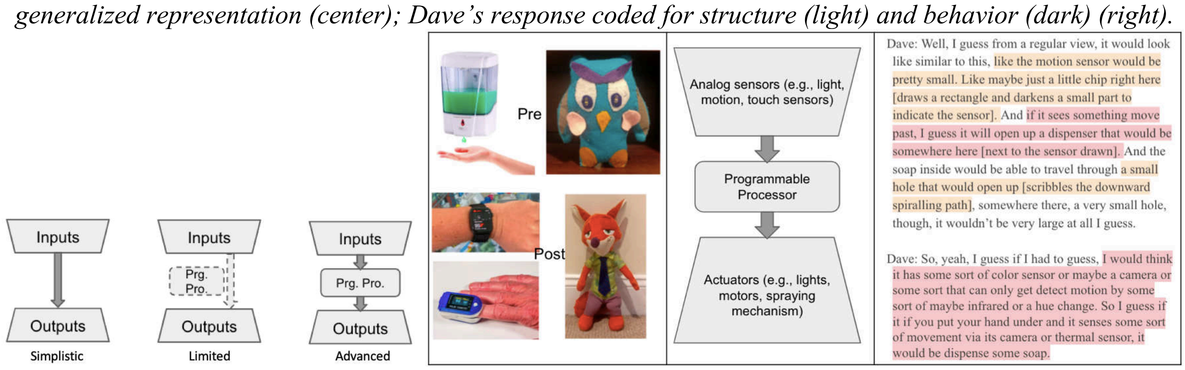
The study was conducted at a public charter high school located in a U.S. west coast city. An experienced high school computing teacher was teaching online an e-textiles unit within the *Exploring Computer Science* course (Kafai et al., 2019). To highlight the internal dynamics of physical computing systems, the teacher infused a variety of additional explanations and learning activities throughout the unit. In this paper, we focus on analyzing shifts in student conceptions about physical computing systems pre- and post-unit. The teacher chose ten of the 24 consenting students (5 male, 5 female; all except one identified as non-White) for interviews. All students were formally learning to program for the first time and had ~10 weeks of *Scratch* programming.

Data collection and analysis

I interviewed students pre- and post-unit to capture their structural and behavioral understanding. Each interview (~20-30 mins each) had two sets of questions: one about the working of a sensor-based everyday device (automatic soap dispenser pre-unit and pulsometer post-unit) followed by another about an interactive toy (see Figure 1, center). All four artifacts were functionally similar, i.e., involved analog sensors and outputs but differed aesthetically (see Figure 1, center). The everyday technologies were not discussed in class and the toys were similar to student e-textile projects but more sophisticated. Students were given the functional description of the artifacts during the interviews and asked questions such as: "what do you think is inside? How do you think it works?". They were encouraged to draw and explain.

Student responses across pre- and post-unit interviews were thematically analyzed for structural and behavioral details (see Figure 1, right). Based on earlier work (Figure 1, left; Jayathirtha & Kafai, 2021), I deductively generated a codebook to identify structural and behavioral details and qualitative distinctions (*simplified, limited, advanced* in Figure 1, left). For instance, structural and behavioral aspects were separated in Dave's response (light and dark shades in Figure 1, right), and each was further classified as *simplistic* since there was no mention of any computation mediating inputs and outputs in the structural or behavioral explanations. Structural explanations that included a computing component but lacked apparent interconnections between parts were categorized as *limited.* Explanations with clear interconnections between computing, input, and output devices were coded as *advanced*. Within behavioral explanations, the mere mention of computing without further details about its role was coded as *limited*, and explanations with any further elaboration about how computing mediates the system behavior were categorized as *advanced*. I, along with another researcher, discussed the codebook and analyzed two students' (20% of the dataset) pre- and post-unit interviews. We agreed upon 15 out of 16 (93.75%) codes and resolved the discrepancy through discussion. We analyzed the rest of the interviews independently, verified their responses (~90% agreement), and clarified discrepancies.

Figure 1
Representation of categories of student conceptions (left), Pre- and Post-interview artifacts and their generalized representation (center); Dave's response coded for structure (light) and behavior (dark) (right).



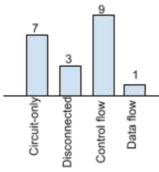
We further inductively analyzed (Creswell & Poth, 2016) behavioral explanations and captured four key themes: (a.) behavioral descriptions which involved only circuit-based mechanisms; (b.) explanations that treated programs and circuits as disconnected; (c.) explanations that only accounted for control flow (such as basic conditional logic) within the systems; and, (d.) descriptions that include both control and data/information flow between programs and circuits during program execution. The first two closely overlapped with *simplistic* and *limited* explanations. The latter two themes were evident within the *advanced* category, i.e., accounted for computing but by highlighting different aspects of its dynamic nature. The same researcher was presented the themes and example excerpts from student responses who agreed with most of them (85% agreement). Disagreements were resolved through discussion.

Findings

Overall, students' structural and behavioral understanding of sensor-based devices and toys shifted from simplistic or limited pre-unit to advanced post-unit (see Figure 2, central table). Pre-unit, structural explanations were mainly limited to input and output devices. Behavioral explanations either involved only electronic interactions between circuit elements or accounted for control flow similar to conditional logic in *Scratch.* However, post-unit, structural explanations included computational components and clearer interconnections. Further, behavioral explanations included data flow details involving sensor values and their processing.

Figure 2

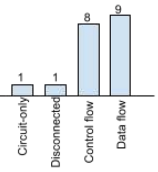
Distribution of student responses across structural and behavioral details (table) and themes and frequencies within behavioral explanations pre- and post-unit (graphs either sides).



	Pre-unit (40)				Post-unit (39)*		
	Simplistic (18)	Limited (11)	Advanced (11)		Simplistic (2)	Limited (8)	Advanced (29)
Structure (40)	○○○ △△△△△△△	○○○ △△	○○○○ △△		△	○○ △△	○○○○○○○○ △△△△△△△
Behavior* (39)	○○○○○ △△△△	○○ △△△△	○○○ △△		△	○ △△△	○○○○○○○○○ △△△△△

△ Everyday device explanations ○ E-textile toy explanations

* One student, Meena, did not provide behavioral explanation for pulsometer
Numbers inside the parenthesis indicate frequencies of the codes



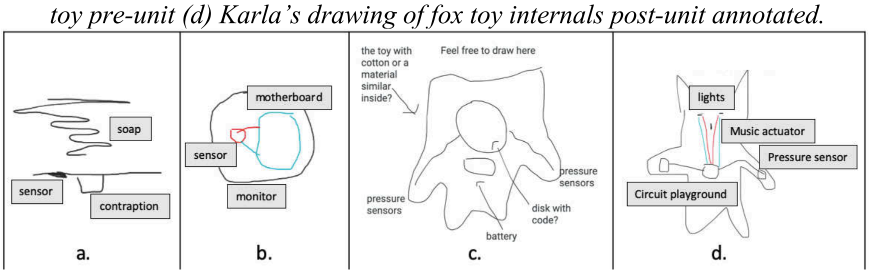
Towards advanced structural understanding

Most structural explanations pre-unit missed computing, more so in the case of automatic soap dispensers (Figure 2, Simplistic column along Structure row). Although the toy's structural composition was more accessible pre-unit, most responses still lacked interconnections between different components (14 out of 20). However, post unit, students' structural explanations across artifacts involved a computational component and interconnections (table in Figure 2, Structure row). Most descriptions included computing-related components such as "motherboard" and microcontrollers, and drew interconnections between input, output, and processing unit.

Across both interview artifacts, explanations about structural composition got more sophisticated post-unit. Pre-unit, more than half of the explanations (14 out of 20) missed any computing component or included one without a clear role. For instance, in pre-unit, Dave described the internals of the soap dispenser as involving only a sensor and a mechanical "contraption" for letting the soap out (Figure 4, a.; 020521, pre-unit). These explanations are unlike Karla's pre-unit response that involved a "disk with code" connected to the "pressure sensors" at the hands of the toy bird, without any connections with the "disk" (Figure 4, c.). However, at the end of the unit, most descriptions (15 out of 20) involved a separate microcontroller connected to input and output devices. Besides structural composition, there was a significant difference in how students explained interconnections post-unit compared to pre-unit. Unlike mentioning different parts without interconnections pre-unit, students made more elaborate connections post-unit. For instance, in his description of how a pulsometer works, Dave clarified that the sensor and the screen will be connected to the "motherboard" to receive values and display them onto the screen. This is comparable to Karla's explanation post-unit involving microcontroller and actuators with definite interconnections (Figure 4, d.).

Figure 4

(a) Dave's annotated drawing of internal structure of an automatic soap dispenser pre-unit; (b) Dave's pulsometer internals post-unit annotated; (c) Karla's structural drawing of the bird toy pre-unit (d) Karla's drawing of fox toy internals post-unit annotated.



Towards advanced behavioral understanding

Unlike structural understanding, pre-unit, students' conception of both systems' internal behaviors was simplistic or limited (Behavior row in Figure 3). However, post-unit, this shifted to more advanced understanding within behavioral descriptions across the everyday technologies and e-textile toys, more pronounced in the case of the toy. Further, students included more data and control flow details in their internal working explanations post-unit.

Before the unit, most behavioral explanations (15 out of 20) were either simplistic or involved computing in a limited fashion. For example, Santos explained the underlying mechanism for the toy as "two pieces of wires, when squeezed, touch and send a signal to the light. They turn brighter when you squeeze them harder" (022421, pre-unit). However, post-unit, students' explanations involved more computational details, moving between the different layers of abstractions between the hardware and the software. Most (15 of 19) descriptions had computing mediating data flow between the input sensors and the actuators such as LEDs or the display; only 5 of the 19 explanations were simplistic or limited. Overall, learners more often acknowledged the role of programs in controlling the behavior of the system post-unit.

Students' behavioral explanations, post-unit, moved from predominantly circuit-based or control-flow-based to more data-flow-based (see Figure 3, graphs on either side). Pre-unit, a majority either involved only circuit-related aspects (7 out of 20) or treated circuit and program as separate entities (3 out of 20) or explained in terms of conditional control flow, drawing from *Scratch* they had just learned (9 out of 20). However, post-unit, students better articulated the mediating role of computing within these artifacts, at least in one of their explanations. A majority of explanations (9 out of 19) included some form of computation with numerical values produced by the sensors and programs as comparing values to make decisions for outcomes or performing arithmetic operations on them such as counting or incrementing based on the pulses sensed. However, a small proportion of students (2 out of 10) struggled to explain the behavior of the pulsometer.

Discussion

Students moving towards constructing advanced explanations of the internal dynamics of everyday devices and interactive toys post-unit is promising in a few ways. Unlike prior studies that reported school students across a wide range of ages having difficulty unpacking everyday devices (e.g., Cederqvist, 2020), our results noted that high school students within physical computing unit shifted their conceptions. However, given that this was one of the first studies exploring changes in learner conceptions across a semester-long unit, more work is needed to examine the role of curricular projects, the curriculum, and the context of e-textiles in deepening student conceptions about the inner workings of physical computing systems.

Analyzing students' structural and behavioral conceptions illuminated specific aspects of this conceptual shift. Learners not only developed a more detailed understanding of the structural composition and connections, but they had also developed a language to talk about different layers of abstractions between the hardware and software. Such a trend can be considered a step towards understanding the underlying designs of everyday devices that embody social injustices (e.g., Costanza-Chock, 2020). Thinking about the internal dynamics of devices such as automatic soap dispensers or digital pulsometers in terms of sensor values and their processing makes room for critical questions such as who's data is included and excluded in the device design and what are the implications for different user groups. Such questions can lead to recognizing how social aspects such as race, gender, sexual identity, etc., intersect with the design of these devices and developing computing literacy required to advocate for actionable design changes within everyday computing systems (Costanza-Chock, 2020).

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