Designing Visible Engineering: Supporting Tinkering Performances in Museums

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ABSTRACT
Interactive technologies like multi-touch tables have enabled museum exhibit designers to support visitors’ learning with a wide range of resources (from multimedia to dynamic feedback to the presence of other visitors). Designers must make decisions, though, concerning how best to align the affordances of these resources with the learning activities they are trying to support [23]. This work examines a multi-touch table exhibit designed to support an activity, tinkering, which has been identified as a form of interaction that may offer special benefits to novices learning about engineering [e.g., 4]. When a learner is tinkering, he or she is engaged in a process of iterative adjustment to a constructed artifact, making use of “just in time” resources and feedback to guide the next steps in their exploration of the problem space. The exhibit studied in this work provided several resources for supporting tinkering, and this paper presents a detailed case showing how these different resources (some technical, some social, and some sociotechnical) were or were not used by learners. A key design goal we identified was the need to transform the tacit engineering practices of visitors into visible engineering performances, such that those performances could serve as “cultural tools” [35] for mediating the learning of other visitors.

Categories and Subject Descriptors
H.5.2. [Information Interfaces and Presentation]: User Interfaces; K.3.1 [Computers and Education]: Computer Uses in Education - Collaborative learning

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Design, Human Factors.

Keywords
Museums; exhibit design; learning; engineering education; multi-touch tabletops.

1. INTRODUCTION
Museums devoted to Science, Technology, Engineering, and Mathematics (STEM) topics have, much like formal educational institutions, begun to recognize that the methods by which we teach engineering may need to be distinct from how we teach science [30]. The main differences seem to lie in the distinctions in disciplinary practices between engineers and scientists. A “disciplinary practice” is a way of going about things (usually a mix of both orientations and actions) that is common to or emblematic of a particular field. For example, activities like tinkering, wherein learners playfully explore a problem space by iteratively adjusting and testing an artifact they are constructing, is a disciplinary practice that may hold special benefits for learning about engineering [4], which places a much stronger emphasis on the iterative refinement of problem definitions and development and testing of solutions [30]. Tinkering is a practice engaged in by both novice and expert engineers, often for many of the same reasons, like how can tinkering help one simultaneously refine both the problem definition and the solution when facing a new challenge [4, 8]. As such, developing educational interventions that focus on tinkering can engender authentic disciplinary practices in novices [4].

Tinkering is very much in keeping with the learner-centered, constructivist pedagogy found in many hands-on science museums [2], but helping learners productively engage with this disciplinary practice requires different design strategies. For example, many hands-on science exhibits are designed to illustrate a specific scientific concept or phenomenon. For this reason, many hands-on science exhibit experiences follow a common template: visitors approach the exhibit, read (or have read to them) a short label that instructs them on what to do, perform the prescribed action, and then read another label that helps them interpret the outcome of their action. Visitors have largely become acculturated to this template, as evidenced by the fact that most visitors ask “what does this do” when first approaching an exhibit at a science museum [5]. Of course, many hands-on science exhibits are designed to allow and to encourage more extended experimentation, but experimenting with a scientific phenomenon (like electric current, or magnetism, or gravity) is very different from employing a scientific phenomenon to attain goals, as occurs within engineering.

We argue that to create an engineering education exhibit, designers should attend to how to engage visitors productively with disciplinary practices endemic to engineering. To foster productive disciplinary engagement, learners should be encouraged to engage in problematization, should be given the authority to address the problems they have taken on for themselves, and should have their efforts subject to some form of accountability [10]. Appropriate resources are then needed to support these three aspects of productive disciplinary engagement.
Resources can take many forms in an interactive exhibit, from designed elements (like multimedia, interaction designs, feedback mechanisms, etc.) to social elements (visitors often draw upon one another as resources when they interact with exhibits). Of course, the special challenge for exhibit designers lies in making these resources visible to visitors – visitors must see what is possible within an exhibit to be able to appropriate resources [13]. To illustrate how resources can be designed to support productive disciplinary engagement, and how these resources are appropriated by visitors, this paper presents a case drawn from data captured from an engineering exhibit installed in a hands-on science museum in a major city. By combining log files of the actions visitors take with the exhibit, transcriptions of visitors’ talk, and coded videos of their gazes and use of exhibit space, we are able to illustrate the complex interplay of technical and social resources learners draw upon to engage in productive tinkering.

With this work we show how careful museum exhibit design can make the varied socio-technical resources at a multi-touch table engineering exhibit more or less visible to visitors, and provide recommendations for how engineering practices can be transformed into visible, collaborative engineering performances in informal settings.

2. BACKGROUND & PRIOR WORK

It is important to distinguish between practices and performances because many practices contain aspects that are tacit or hidden to novices. We define an “engineering performance” as an engineering practice that is demonstrated in a fashion that allows the core components of the practice to be visible to an observer. While in many instances when we say something is “visible” we do mean that it can be perceived via sight, we are not using the term strictly literally. Rather, when a component of practice is described as visible, we intend that it can be readily perceived by learners. Designers have a great deal of power in deciding which elements of a practice to make visible to learners. In this section, we review how designers’ decisions regarding visibility are known to affect learning.

2.1 The Educational Value of Visible Performances in Museums

Museums, especially interactive science museums, are often designed with spectatorship in mind, in the sense that visitors should be given an opportunity to see how other visitors are making use of an exhibit. It is common for visitors to “lurk” and observe what other social groups are doing at an exhibit before approaching it themselves [34]. We claim that when an exhibit design allows spectators to “tell what’s going on” by watching other visitors’ performances, they can gain advance knowledge about the exhibit that will help them engage in problematizing, one of the design principles recommended for encouraging productive disciplinary engagement [10]. Problematization can be defined broadly as when learners “define problems that elicit their curiosities and sense-making skills” [14, p. 12]. Here we will discuss how visible performances can support these two aspects of problematization.

2.1.1 Eliciting Curiosity via Expressive Performance

Whether or not a spectator can “tell what’s going on” depends not just on how obvious exhibit designers can make the exhibit’s current state (e.g., via design strategies like large secondary displays), but also on how obviously the operating visitor’s actions are affecting the exhibit’s current state: in other words, spectating visitors need to be able to witness the operating visitor’s performance at the exhibit. Human-computer interaction designers have explored how the obviousness of connections between user actions and the system’s responses can affect spectatorship - when these connections are obvious the design is dubbed “expressive” [28]. The value of expressive design for engaging the curiosity of spectators has been borne out in in situ studies of visitors interacting with computer-based exhibits [24]. In one simple example, visitors’ exaggerated reactions to a mild electric shock administered by an exhibit titled Do Not Touch were seen to draw the attention and curiosity of other visitors. A loud zapping sound reinforced the connection between visitor action and system reaction. Although minimally expressive, the design’s clear pairing of action and reaction immediately communicated how visitors could expect to approach the exhibit.

2.1.2 Mediating Meaning Making via Expressive Performances

Expressive performances also allow spectators to become more deeply engaged in shared sensemaking around the activity, whereas other models of spectatorship (“secretive,” where both user actions and effects are hidden, or “magical,” where the user actions are hidden but the effects are visible, per Reeves et al., 2005) mitigate engagement. In recent work, Yoon et al. [37] were able to enhance the learning potential of existing hands-on exhibits by making the experiences less “secretive” and more “expressive” by revealing previously hidden effects via augmented reality. For example, when a visitor completes a physical circuit by touching two metal posts, the path taken by electricity in the circuit is highlighted by projecting a computer animation onto the exhibit workspace (and onto the performing visitor). Without the digital augmentation, it would have been harder to structure group discussion and activity around the phenomenon, as the phenomenon would have been invisible. With the augmentation in place, students reported that they found being able to work in groups to be the most helpful scaffold (i.e., learning support) present in the exhibit. In other words, the augmentation activated the possibility of group work. The expressive performance is effectively a “cultural tool” [35], meaning that the visible performance is a resource that learners can appropriate for their own needs (in this case, in service of shared meaning making).

2.1.3 Expressive Performance and Productive Disciplinary Engagement

Exhibits can be designed to produce expressive performances, and these performances have been shown to be useful in eliciting visitor curiosity and in mediating social meaning making among visitors. Curiosity and sense making are required for learners to engage in problematization [14], a key component of productive disciplinary engagement [10]. For a performance to be expressive, though, exhibit designers need to make design decisions about (1) the visibility of the exhibit state and (2) the visibility of visitor actions. For example, in the augmented reality circuit of [37], which elements of the exhibit’s state should be visible? Just the path of the current, or the direction of current flow? In the case of the Do Not Touch exhibit [24], should the designers rely only on the performative reactions of the visitors to illustrate the exhibit functionality? (In fact they did not – they added a very loud zapping noise to reinforce the connection between visitor performance and exhibit state). These design decisions must be informed by the educational goals of the exhibit, as different pedagogical goals affect which elements should be most visible, and when they should be made visible, as the next section will address.
2.2 The Role of Visibility in Engineering Education

Electrical engineering is rarely visible to those who are not looking for it. That is, it is hard to incidentally notice (say) Very Large Scale Integration (VLSI) circuit design, and LabView (software used for specifying control systems) is rarely projected on a large screen for spectators. Even if it were visible, it would likely overwhelm novices: many tools that make the materials of engineering visible are designed to be used by experts, who have enough background knowledge and experience to know to which aspects of the presentation they should attend. Even if these presentations were comprehensible, novices would have no idea what to do next—in these tools the disciplinary practices of engineering are often completely tacit. If learners need to seize the authority to engage in problematization and seek accountability for their solution approaches, all key components of productively engaging in a disciplinary practice, what aspects of that practice should be made visible, and how? This section will review what we know about the disciplinary practice of tinkering, and which aspects of this practice might be candidates for incorporation into expressive performances in a museum exhibit.

2.2.1 Hidden Aspects of an Engineering Practice: Tinkering

As per Berland et al. [4], tinkering has been defined in various ways by researchers but basically falls into two classes of definitions: 1) the iterative refinement of problem orientations & solutions, or 2) the iterative refinement of problem solutions. In both senses, productive tinkering appears to require the opportunity for evolutionary iterations on both a problem space (often called ‘local goals’) and rapid feedback for attempted problem solutions (such as compiler errors for computer programming). As such, an exhibit that supports tinkering should enable visitors to engage in iterations that provide rapid feedback on both local goals and the value of the current problem solution. According to Berland et al., successful tinkering events can both enable learning more complex technical content and engaging with new technical content creatively. It should be noted that some researchers have questioned whether or not tinkering is a valuable practice for novices, claiming that the ad hoc trial-and-error nature of tinkering can cause more problems than it solves [21]. These negative effects of tinkering seem to occur only when the tinkering is haphazard, however. Tinkering can be quite helpful when novices are more systematic [27]. The key, then, to making tinkering productive for learners seems to lie in providing real-time feedback, so that learners can more carefully monitor and manage their tinkering progress. This allows them to engage in “just-in-time” planning that gradually evolves how they understand both the problem space and their solution.

2.2.2 Just-in-Time Tinkering Feedback

We argue that for a museum exhibit setting, the nature of the “just-in-time” feedback should encompass information on (a) the materials at hand to build a solution to the problem, (b) processes for employing those materials, (c) the current “state” of development of the solution-in-progress, and (d) the degree to which the current solution satisfies the problem. Visitors will not want or need to know all of this information at once; visitors should be able to access the information when it becomes most salient for them. The question remains: what design strategies can we use to make these aspects of the engineering learning experience more visible, so that when they become salient for the learner she or he can appropriate them to support productive tinkering?

2.3 User Interfaces to Make Engineering Practices Visible

We are making use of a multitouch table with tangible blocks in our exhibit, so this review will focus on closely related technologies. This section will review how the four types of tinkering feedback identified in the prior section (materials, processes, state, and solution satisfaction) can be made visible via the affordances of different types of user interfaces. Because museums are social environments, we will also attend to how different technology designs can encourage social processes (either via conversation or via “expressive performances,” per section 2.1) to make these types of feedback more or less “visible” to learners.

2.3.1 The Affordances of Tangible User Interfaces for Providing Just-in-Time Feedback to Learners

Tangibles have been shown to be a profitable way to increase the visibility of computer programming and engineering work in a museum context, but the work is nascent. Wyeth [36] and Horn [17] used tangible blocks to engage younger children in rudimentary programming work, and Sifteo [25] blocks have also been used to teach basic visual programming. One obvious advantage for tinkering is that the materials available for use, are, well, material: the tangibles are present for inspection and sorting, and there are no elements “hidden” within menus or by the need for fluency with the reserved words of a programming language. Compared to traditional programming on a small computer screen, the use of tangibles offers a larger “display space” for tinkering and also allow for a ‘conversational’ style of interaction, allowing learners to proceed in small steps, to quickly test their ideas [18, 17]. This can allow fellow participants (or spectators) a clearer lens into the state of individual users’ solutions-in-progress, to provide assistance or to help forward their own solution designs.

Some tangible projects, such as “snap together circuits” (e.g., lightup.io, snapcircuits.net), are often designed to provide feedback on the processes for employing them (e.g., the connection points of each component have a clear “fit” with others), which can reduce time spent by users to figure out the basic mechanics of the interface, and allow them to focus on their designs and problem solutions. However, such purely physical interfaces lack the kinds of automated feedback available from computers. This can make it very difficult for spectators to engage with the problem space, as understanding the structure (which the placement of the tangible elements conveys) is only part of the challenge for understanding the current state of the activity: spectators (and learners) must also understand the consequences of the structure. In other words, the construction experience needs to be made “expressive” [28] not just in terms of the direct action-effect pairings (e.g., a learner’s action moves a block) but also in terms of the more distal action-effect pairings (e.g., a learner’s movement of a block results in a completed circuit) that are indicative of progress towards solution satisfaction.

2.3.2 Interactive Tabletops to Support Collaborative Sense Making and Feedback

Recent research has shown that the use of interactive tabletops can enable learners to quickly create a shared understanding of the task, and engage in more problem-specific collaborative discourse and problem reasoning than with similar paper-based approaches.
[15], to see where their peers were having difficulties and offer more suggestions [11] than with paper-based or individual (e.g., tablet) devices. Similar to the use of tangibles in a shared workspace [31], the use of tabletops in museum spaces has the potential to increase the ability of spectators and fellow participants to monitor and provide feedback to others.

When combined, tangibles and interactive tables can also offer new forms of user feedback. Working in concert, the interactive table can extend the functionality of the tangibles by adding a layer of augmented reality. By responding to the placement of tangibles on its surface, the table can provide additional real-time information about the artifacts the tangibles represent, the linkages between the different objects, or reflect changes in users’ tinkering [9, 29]. The combination of tangibles and interactive tabletops offers designers more flexibility in developing feedback for participants based on the state of their current solution and the degree to which it satisfies the problem.

2.3.3 Ambient and Aggregate Displays for Persistent Feedback and Monitoring

Researchers are increasingly considering how users’ locations within the room, and the location of ambient and aggregate displays can affect and support their learning and inquiry [26]. The use of Multiple External Displays (MERs) can help scaffold participants’ tinkering and investigation by aggregating their individual and collective actions, as a means for providing feedback and helping with self-regulation [1, 33, 20]. The advantage of such displays is that they can sit at the periphery of learners’ attention, only requiring their attention when needed [3, 7]. This allows for more flexible appropriation of their use within the flow of a learning activity [6].

3. DESIGNING AN ENGINEERING EXHIBIT FOR VISIBILITY

![Image](image1.png)

Figure 1. Oztoc concept art. Visitors must engineer glowing fishing lures to attract bioluminescent aquatic creatures.

3.1 Oztoc Game Design

In order to address our project goals we developed a multitouch tabletop exhibit that is installed at a large urban interactive science museum. The exhibit, named Oztoc, situates participants as electrical engineers called in to help fictional scientists who have discovered an uncharted aquatic cave teeming with never-before-documented species of fish (see Figures 1 and 2). The aquatic creatures who live in this cave are bioluminescent, and the visitors are asked to help design and build glowing fishing lures to attract the fish so that the scientists can better study them. Participants place wooden blocks (see Figure 2), which act as electrical components (i.e., batteries, resistors, Light Emitting Diodes or LEDs, and timers), on the interactive table to create simple circuits. (The table recognizes the blocks via fiducial symbols). Creating a successful circuit (one that has the correct ratio of resistors, batteries, and LEDs) causes the LEDs to glow and lures the fish attracted to that type of light out for cataloging. In order to catch all the different fish, players must experiment with creating circuits with different colors (red, blue, or green) and numbers (one, two, or three) of LEDs.

![Image](image2.png)

Figure 2. Children gathered around the Oztoc exhibit.

![Image](image3.png)

Figure 3. Oztoc exhibit layout.

![Image](image4.png)

Figure 4. Players can assemble virtual circuits using resistor, battery, timer, and colored LED blocks. Circuit connections (depicted as lines on the tabletop) are made by bringing the positive and negative terminals of the blocks (augmentations displayed by the table) in contact with one another

When a circuit is successfully created, a fish will swim up from the depths and head towards it, getting captured and displayed on a large scoreboard screen placed at one end of the Multitouch table (see Figures 2 and 3). Mounted along another side of the
table is a rear-projection screen, which displays a looping video that introduces visitors to the exhibit’s narrative and provides a wordless tutorial on how to manipulate the blocks to form a simple circuit (see Figure 4).

The narrative of the exhibit was developed to give learners a situated context in which to problematize. Many engineering or making exhibits run into trouble by being either too open-ended, effectively paralyzing visitors with indecision, or by being too prescriptive, where visitors are basically tasked with following a set of directions to build a known artifact. We wanted to ensure that the exhibit would give visitors some freedom in choosing their own goals (e.g., which types of fish to target) while still giving them a common set of materials and processes. The tabletop is able to provide feedback on visitors’ emerging circuits, effectively acting as a layer of augmented reality to support players’ exploration and tinkering by showing them critical information.

3.2 Designs to Support Tinkering in Oztoc

We had decided to make four types of information readily visible in Oztoc to support tinkering: (a) the materials at hand to build a solution to the problem, (b) processes for employing those materials, (c) the current “state” of development of the solution-in-progress, and (d) the degree to which the current solution satisfies the problem. Here we review the designed elements that either directly made these features visible or made them visible indirectly by eliciting expressive performances from visitors.

3.2.1 Making Materials Visible

The tangible blocks are the main materials used by the visitors (see Figure 3). Visitors can determine via visual inspection the full range of circuit components that can be used – namely, batteries, resistors, timers, and colored LEDs. To distinguish the blocks, users could refer to either the English text label or the common circuit symbols for the components printed on the blocks. We wanted visitors to come away with some familiarity with the disciplinary conventions for describing circuit materials, so that visitors would be able to transfer such knowledge to real circuit building activities in nearby exhibits.

Additional materials were made visible on the table surface via the table’s graphics, in response to when the blocks were placed on the table or manipulated in certain ways. For example, placing a block on the table causes positive and negative connection terminals to appear on either side of the block, subtly inviting visitors to build connections by tapping positive terminals against negative terminals (more on this in the section below on making processes visible). When a connection is formed, this is indicated by the appearance of a solid line connecting the blocks (see Figure 4) which persists even if the users move the blocks.

The just-in-time appearance of additional materials (terminals, connection “wires”) occurs only when the user would have the occasion to use the material. It was one way we ensured that the visible materials would appear when salient, so that the learner’s problematization could evolve from the initial exploration of the blocks to encompass how to make use of them (the process, covered in the next section).

3.2.2 Making Processes Visible

The main processes in this task involve connecting circuit components or disconnecting components from one another. (Note that a process, as we define it, is a lower-level construct than a practice: it is an “atomic”-level action that can be performed in the space without any associated strategic intent. Debugging, which carries with it some strategy, would be an example of a practice.) As mentioned in the prior section, the just-in-time appearance of the positive and negative terminals as blocks are placed on the table was intended to hint that a connecting process was need to add another material (a wire) to the circuit. We have one other support to increase the visibility of the process of making connections: a looping tutorial video projected on a screen behind the table, which demonstrated the process of connecting a simple three-element (LED, resistor, battery) circuit, and how to remove connections by swiping one’s finger across the connection line. Note that the tutorial is a wordless demonstration of process, to echo the learn-by-observation pedagogy that watching other visitors provides.

3.2.3 Making State Visible

The “state” of a visitor’s solution is described by the current assemblage of the circuit elements. The design decisions we made concerning materials contribute to the visibility of the circuit states: visitors can see which tangible blocks are on the table by reading their labels or recognizing their symbols, and can discern the connectivity of the circuit by looking at the connection lines. When a circuit is fully connected, two additional just-in-time state indicators appear: current animations and “power indicators”. The connection lines become animated waves to indicate that current is passing through them (see Figure 4). LED blocks are augmented with a small rectangular “power indicator,” which shows if the voltage drop across the LED is too low or too high (with a warning that the LED will soon overheat). If the correct amount of voltage is supplied, a colored glow will appear under the LED block (see Figure 4). Visitors can use this mix of visible materials and indicators to diagnose the current state of their (and their companions’) circuits. State diagnosis is a core component of understanding a potential solution; the other component involves evaluating how well the solution’s state satisfies the current problem definition, as the next section will describe.

3.2.4 Making Solution Satisfaction Visible

A solution is partially defined by its state, and partially in terms of how well the state satisfies the current problem definition. For learners to productively tinker, they must also be able to tell how close a solution is to meeting the problem definition. That said, we expect problem definitions – and thus the degree of solution satisfaction – to evolve over time, as the learner becomes more acquainted with the materials, processes, and states of the problem space. So some of the visible design elements (e.g., the appearance of connection “wires”), can serve as visual indicators of solution satisfaction, if the current problem definition is limited to figuring out how to connect blocks to one another.

Our design provides additional solution satisfaction indicators in addition to the ways learners can appropriate the visible materials, processes, and states to make judgments about lower-level solution satisfaction. For example, when a circuit is completed and functioning, an animated fish surfaces and charges towards the circuit/lure, accompanied by attention-getting sound effects and a flash when the fish is “caught” by the circuit. This communicates that the state of that circuit can be associated with a given fish type, feedback that is reinforced by displaying the just-caught fish on the scoreboard display (see Figures 2 and 3). The scoreboard also displays the identity of the player who caught the fish (the table is divided into 4 named play spaces). We associated the captured fish with the player identities primarily because of the known importance of action attribution in exhibits (see Section 2.1) – visitors need some way of matching circuit designs to fish types. The association of fish with player also serves the purpose of supporting accountability: according to the literature
on productive disciplinary engagement, learners need to have their efforts subject to community judgment.

The scoreboard also displays a certain number of “points” associated with having caught fish. More points are awarded for fish that are attracted to more complicated circuits, although there is a small amount of random variation to make clear that the captured fish are not singular, but rather, are just sample specimens. The intent behind awarding points was to motivate visitors to tinker with creating different kinds of circuits. We anticipated that some visitors would rely on their familiarity with game conventions to revise the problem definition to include competition over fish.

The scoreboard layout itself can also serve to motivate further circuit exploration. It implicitly organizes the problem space, by providing open, empty squares for each of the 18 possible aquatic creatures, which can vary in color (Red, Green or Blue), size (Small, Medium, or Large), and type (Finned or Tentacle-bearing). The intent was for learners to use this structure to scaffold their evolving problem definitions, by allowing them to view the pattern of caught fish and missing gaps to (1) realize that undiscovered creatures were still out there awaiting specialized lures, and (2) reason about what circuit design variations might lure in those undiscovered creatures.

4. Methodology and Participants

Ozloc is installed in an enclosed exhibit space just off the main floor of a major metropolitan science center. A lollipop sign just outside the exhibit space indicates when videotaping will take place in the exhibit, so visitors are free to decide to enter or to return at a time when data collection is not active. Researchers were present around the corner from the multitouch table (see Figure 3), so that they would not be obtrusive, but they would be available in the event of equipment trouble. Video data was collected via an array of cameras placed in the exhibit space, and audio from a boundary microphone. Visitor interactions with the table were logged using the ADAGE system [32].

The video data was transcribed using InScribe, and was coded in to indicate times when visitors directed their visual attention to either another player’s spot on the table, the tutorial, or the scoreboard. Two researchers performed the coding, and resolved any disagreements through discussion and by consulting the other camera angles. The log file data and the video data were manually synchronized and combined to create the graphs that support this case analysis.

The main case we present here was selected from two days of data collection wherein 152 visitors had approached the exhibit. We used observations recorded by researchers, log files, and a review of the collected video to select the case. Because we wanted to illustrate how visitors could make use of the multiple exhibit resources to engage in the circuit building activity, we looked for a case where: more than two visitors were present, the visitors knew one another, every member of the group completed at least one successful circuit, and each major element of the exhibit was attended to by at least one visitor. Only one case met all of these criteria. (Ongoing work is examining the representativeness of different visitor behaviors, but anecdotally speaking, other visitors engage in many of the behaviors illustrated here.) It involves a single nuclear family: a father, mother, and son (who appeared to be around 10 years of age), who will be referred to as Dad, Mom, and Son. They entered the exhibit space of their own free will, and likewise, persisted in their activities until they tired of the exhibit.

The case will present their interactions with the table through the lens of the evolution the Son’s problem definitions and solutions, to illustrate his engagement with the tinkering process.

5. RESULTS

This section primarily presents a single case which, while not necessarily representative of all possible visitors, serves to illustrate how the resources we made available for productive disciplinary engagement in tinkering were (or in some cases, were not) appropriated by users. This detailed account allows us, as designers, to reflect on how to make these resources more visible.

5.1 Problem Definition Phase 1: Discovering Materials & Processes

All three visitors began their interactions with a relatively constrained problem definition, exploring the most immediately visible materials (the blocks) and fairly quickly proceeding into exploring low-level processes (i.e., making connections). Aside from a period Mom spends looking at her companions’ table spaces, the set of resources they consult is tied very closely to their personal workspaces and tangible blocks. In the meantime, Son is very vocal in narrating his activities with the exhibit. His talk indicates that he is still thinking of the problem space in terms of materials and processes, not states - his narration details the connections he has build amongst different components, but he doesn't seem to be thinking about any higher purpose to his actions. To borrow from the Structure-Behavior-Function framework sometimes used to characterize how learners come to understand systems [16], he is working with a problem definition that is really just about lower-level Structures, and has not begun to touch on how those Structures might Behave, let alone how those behaviors might be harnessed to support Functions. For example, some of his narration:

12:47:23 PM: Son: Hey look, a resistor is connected to another resistor

12:47:26 PM: Son: Alright this resistor... so I got to put this battery here, next battery here

5.2 Problem Definition Phase 2: Framing the Solution Structurally

At 12:47:35, Mom looks again at Son’s workspace (see orange circle marking beginning of Phase 2 in Figure 7). Thanks to the visibility of the blocks, she can quite clearly observe which materials Son is employing, but as she reflects the state of his solution back to him, it seems her problem definition is predicated on thinking about the composition of the circuit as a set:

12:47:36 PM: Mom: So you did an LED, a resistor...

This remark seems to push Son to reframe his solution in terms of a set of items, as opposed to a narrative sequence of connection actions (his earlier talk sounded very much like the well-known “Dem Bones” song, where the verses take the form of “The toe bone’s connected to the foot bone, the foot bone’s connected to the heel bone, …”). In Son’s response you can see some lingering narrative description, but he's now accounting for all the elements in his circuit as a set:

12:47:39 PM: Son: Yeah. I connected the battery to the resistor, so now all I have to do is connect the resistor to battery to the LED. Yep, it's all connecting. So I have two resistors connected to each other, and, uh, one, there, of the two resistors is connected to the battery, and the battery is connected to the red LED.
At this point, he has started to view his construction as a singular entity, albeit one comprised of parts.

5.3 Problem Definition Phase 3: Framing the Solution Behaviorally

They experiment for another 30 seconds or so, then Mom asks what the Timer block is for, and this gets Son to evolve his problem definition yet again. He looks over at his mother’s table space (marked by orange circle marking the beginning of Phase 3 in Figure 7), and begins to speculate about the Behavior of the circuit. He introduces the idea of the need to power the circuit. It’s worth noting that the material visibility - the fact that there is a non-critical Timer component on the table - is what allows Mom to open this line of inquiry:

12:48:06 PM: **Mom**: What’s the timer for?
12:48:08 PM: **Son**: There’s a timer? I mean I don’t, why would you need a timer? Awesome, so this is awesome,
12:48:14 PM: **Son**: because I think you’re trying to power a timer,
12:48:18 PM: **Son**: because two resistors and then a battery
12:48:20 PM: **Son**: and then an LED and then a timer, that’s what I think it is.

Son still doesn’t quite have a handle on what the circuit is for, functionally (in fact, timers just cause the LEDs to flash), but he is now framing the problem in terms of supplying power to components. This vocalization may have altered the problem definition of the father, because after a 40 second span of manipulating the blocks, Dad refers to the just-in-time power indicator to further elaborate the problem definition:

12:49:02 PM: **Dad**: The problem is that the “power thing”

Up until this point no one had remarked on the power indicator – it appears that it became appropriated as a resource after Son brought the idea of power into discussion.

5.4 Problem Definition Phase 4:
Incorporating Problem States

At this point, Dad decides to consult another visible resource: he turns to look at tutorial video. His movement is very obvious and catches the attention of the Son and Mom, who also look up at the tutorial (see Figure 5, and orange circles marking early stages of Phase 4 in Figure 7). They all watch it for a bit, then both Dad and Son more or less simultaneously make their first complete circuits about 20-30 seconds later (Dad's is a simple blue, Son’s is a simple Red). The mom is a little slower to engage - she watches what the son and dad are doing.

When the circuit connects (displaying the just-in-time feedback of the wavy connection line) Dad and Mom use this stimulus to remark on the change in state:

12:49:19 PM: **Dad**: Well look at that!
12:49:20 PM: **Mom**: Whoah!

Son starts recapping what they know about the problem definition, clearly treating a circuit as an entity with specific components:

12:49:23 PM: **Son**: So that would mean, resistor and LED

Mom appropriates his problem definition and begins reflecting on her non-working solution:

12:49:29 PM: **Mom**: I have that...
12:49:30 PM: **Son**: Yeah battery resistor...
12:49:31 PM: **Mom**: I have battery

The Son makes use of the visibility of the current state of Mom’s circuit to realize that the circuit is not actually connected. He uses the visibility of the state of his own solution to help give her advice, first gesturing to his own solution (see Figure 6; she begins watching his portion of the table, visible in Figure 7), and then reaching for extra blocks to demonstrate the connection process:

12:49:32 PM: **Son**: Mom, you’re doing it wrong then, because it’s like this... uh, positive to negative like that and then

![Figure 6. Son first gestures to the state of his fully-connected circuit, then begins to pick up block materials to demonstrate the process of connecting blocks.](image)

5.5 Problem Definition Phase 5: Framing a Solution Functionally

At this point, they are all interrupted by an arrival of the first fish to the active circuits (see orange circle in Figure 7). They watch the capturing process and note how the circuits attract the fish. At this point, they have added Function to their problem definition (namely, that circuits exist to attract fish).

12:50:08 PM: **Son**: Oh I got that one, I got that one. Yeah

5.6 Problem Definition Phase 6:
Incorporating Solution Satisfaction Criteria

They watch the active circuit and fish action on the table for another 40 seconds or so, and then the Son looks at the scoreboard (see orange circle demarcating beginning of Phase 6 in Figure 7). The other two visitors notice this and also look at the scoreboard. After a bit the boy makes an observation that will start to change his problem definition yet again, to include the idea that a particular circuit might attract a particular type of fish:

12:50:28 PM: **Son**: Ooh another one, I got two the same. This game is cool.

12:50:44 PM: **Mom**: What does this mean?

12:50:44 PM: **Son**: They love my machine
They are also becoming aware of their identities as “players” in a game:

12:50:46 PM: **Dad:** I’m Player 1, look

Thanks to the visibility of the scoreboard there is now a way for them to get additional feedback on their solutions. They use this to yet again evolve the problem definition, to include points:

12:50:49 PM: **Son:** I have 9 you have none [addressing **Mom**]

It is worth noting that throughout this period of problem redefinition, the Mom has not attempted to construct any solutions. She has been watching the other Player spaces and scoreboard. Only after the Son modifies the problem definition once again, adding the concept of "points", will she be moved to complete her first circuit. During and after this, Son and Dad are watching fish captures and ribbing her on her lack of points. At one point, the mother even pushes back against this new problem redefinition, saying:

12:51:05 PM: **Mom:** I don't need points

A bit later the Dad reiterates the new problem definition:

12:51:12 PM: **Dad:** Look [Mom] you have no points, that's a problem

**5.7 Problem Definition Phase 7: Expanding Solution Satisfaction Criteria**

When Mom finally makes a working circuit, it is worth noting that she makes a simple Green circuit. It seems reasonable to infer that she intentionally chose a green LED to contrast the red and blue chosen by her companions, using the solution satisfaction feedback made available by the scoreboard to fuel her further exploration of the problem space. The Dad and Son’s initial choices of Blue and Red may have been less intentional, since they worked on their circuits at the same time.

Throughout the period where the Boy and Dad ribbed the mom for not having points, and encouraged her to adopt the new problem definition, they were attending to how many points each of them were earning. Son gets frustrated with not getting more points despite catching so many fish, because each new fish of the same type merely replaces the last-caught fish of that type in the scoreboard, at one point saying:

12:52:12 PM: **Son:** See it won’t add any of my points, it won’t add any of my points

This observation of the unsatisfying solution feedback seems to spur Son to redefine the problem definition yet again. He realizes that he might need to try a new color LED. When he tells Dad that he's going to use another LED, Dad observes the Son grasping a blue LED, and uses that information to ask him if he's trying to make a purple light (this is not actually possible in the game). Son explains to Dad that he's merely swapping out the red LED for the blue, and Mom - who has been seemingly slow this whole time to innovate with her own circuit design - nonetheless explains the logic of different colors attracting different fish:

12:52:21 PM: **Son:** I’m going to take this LED light

12:52:24 PM: **Dad:** Purple?

12:52:27 PM: **Boy:** No I changed an LED light

12:52:29 PM: **Mom:** Well you know it has something to do with your connection though what you attract

Son captures a blue fish (and obtains the extra points he was hoping for), and Mom does some innovation of her own just afterwards, switching from a green LED to a red LED (marked by orange circles at the end of Phase 7). From this point forward the visitors largely keep operating with this problem definition – that they are attempting to attain maximum points, and that they can do so by varying their circuit designs. The Dad in fact engages in an attempt to build a quite large and elaborate circuit, but he does not succeed before they decide to leave the exhibit.

**6. Discussion**

**6.1 Visibility of Materials**

The case above illustrates how readily the visitors make use of the visibility of the materials, quickly adopting the labels printed on
the blocks (“resistor”, “LED”) even when they do not know what
the block is (e.g., the “Timer”). The easy inspectability of
the materials allowed the family to easily see what materials were
available, and as their problem definitions expanded, to use this
visibility to help them diagnose the states of each other’s solutions
(as when Son recognizes what is wrong with his mother’s circuit).
The arrangement of materials in the visitors’ circuits is an
expressive performance of sorts – the mom can inspect his
arrangement of connections to better understand the state of his
circuit, and hers.

6.2 Visibility of Processes
Some players are better able to infer process than others – the
Son, for example, very quickly understands how to connect
blocks. The Mom needs to watch the tutorial and watch the
performances of her companions before she masters the process
of connecting blocks. These different styles might be emblematic
of different ways of approaching authority: Son seems
comfortable taking ownership of the problem space, while Mom
seems to want to have someone else (either the museum, or her
companions) help her understand what the problem definition is.
In her case, the visibility of the tutorial, and her companions’
performances, allow her to eventually master the processes
involved in circuit building and eventually innovate solutions on
her own terms, but this serves as a valuable reminder that not all
visitors will approach the components of productive disciplinary
engagement (of which adopting authority is one) in the same way.

6.3 Visibility of States
The virtual feedback we built into the table (the power indicators,
the wavy connected lines indicating current flow) eventually came
to be discovered and used by the visitors to diagnose the states
of their circuits. This took about three minutes of interaction time
with the table for the visitors to discover, however – arguably too
long. We have seen some visitors leave the exhibit before they
ever get to the point of being able to recognize the states of their
partial solutions. Arguably, we should draw more attention to
these features, perhaps by adding in a more dynamic form of
feedback to visitors.

6.4 Visibility of Solution Satisfaction
Although the visitor group did eventually start using the
additional resources made visible by the scoreboard to revise their
problem definitions, they didn’t take nearly as much advantage as
we would have hoped. This group, like many others we observed,
only ever explored 2 or 3 different circuit design variations (of the
18 possible). We suspect that capitalizing on the desire of many
visitors to get a high score might help encourage further exploration (for example, making the full tallies of scores more prominent), but there is also the risk that this design strategy may not work well for all visitors. The mother, in particular, seemed to
resist being co-opted into a score-driven problem definition she
didn’t embrace or enjoy, a pattern of behavior seen in other
collaborative museum exhibits [22].

It may be the case, however, that some visitors are just more
comfortable playing a “facilitator” role while at museums [12].
The mother certainly fulfilled this in several instances: asking
probing questions that helped her son revise his problem
definitions, and summarizing insights about the problem
definition for the whole group. More work is needed to determine
if there may be alternative ways to motivate visitor explorations,
and to what extent it is necessary to try to motivate all visitors.
That said, women are underrepresented in engineering, so we
should be careful to determine if participation patterns are linked
to gender, as has been seen in other exhibits with elements of
competition in the design [22].

7. CONCLUSION
Tinkering towards actual, practicable goals is both vital to
learning engineering practices and notably hard to support in a
museum structure. As museums have put “Maker Spaces” on their
floors, they have realized that completely open workspaces are not
as effective as carefully bounded (and often facilitated) activities,
a finding consistent with many critiques of open-ended inquiry
learning [19]. In this work, we have shown that radically
increasing the visibility of tinkering resources – whether
technical, physical, instructional, or socio-technical – is a strategy
for supporting making that does not require museums to use their
authority to overly define problems for visitors.

When engaged in the engineering disciplinary practice of
tinkering, problem definitions and problem solutions evolve. This
evolution in problematization demands that the learner
appropriate different resources as they claim authority over their
problem definition and to seek accountability for their problem’s
solution. Children, in particular, seldom get many opportunities to
claim ‘authority’ over problems by engaging deeply with them
and seek ‘accountability’ for their approaches to those problems.
Thus, to encourage children to tinker, designers need to reduce
barriers to resource appropriation, as we have done with visible,
just-in-time tinkering resources. In particular, the case we present
here demonstrates how the resources made available can support
expressive visitor performances, which in turn can serve as
resources to support the tinkering of others. In this scenario, the
child both relied on his parents’ performances to discover new
aspects of the problem space (following his father’s lead in
attending to the tutorial, and noting his parents’ use of differently-
colored LEDs to deduce how to expand his own “catch”), and
engaged in expressive performances of his own (like
demonstrating to his mother how to connect blocks). This mutual
authorship is yet another way to help children feel comfortable in
claiming authority over the problem space. By transforming the
tacit engineering practices of visitors into visible engineering
performances, we found that those performances could serve as
“cultural tools” [35] for mediating the learning of other visitors.

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