Collaboration Through Documentation: Automated Capturing of Tangible Constructions to Support Engineering Design

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ABSTRACT
In this paper, we present and evaluate the design and learning affordances of Mechanix, an interactive display for children to create, record, view, and test systems of tangible simple machine components. By documenting children's interactions, Mechanix provides opportunities for children to learn from user-generated examples and to reflect on their own designs. Through a series of user studies with children, we examine the system's capabilities for documenting tangible design work, facilitating social learning and collaboration, and providing distinct entry points that appeal to a broad range of learners. Our results illustrate the potential of incorporating automated documentation with tangible toolkits to support learning about physics and engineering systems design.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Input devices and strategies, interaction styles*; K.3.1 [**Computers and Education**]: Computers Uses in Education—*Collaborative Learning*

General Terms
Design

Keywords
Tangible interfaces, constructionism, example-based learning, engineering design

1. INTRODUCTION
Post-secondary engineering education has increasingly emphasized hands-on design projects as a way to introduce and solidify the understanding of fundamental engineering principles. While these initiatives have begun to reach high-school after-school programs, studies suggest that complex problem-solving skills can be fostered in even younger students through active participation in engineering design [31, 5]. One avenue for early exposure is software-based simulations, which offer dynamic and extensive exploration through the construction of virtual systems. However, these are often limited by idealized content and interactions with traditional computer input devices and peripherals. Tangible construction kits such as Legos provide children with engaging, intuitive, and flexible design opportunities through their modular components, but designs created with these toolkits are often ephemeral and may be difficult to reconstruct without careful documentation. Consequently, many children do not enjoy the inspiration and growth that stem from exploring the works of others or revisiting their own designs.

Figure 1: Child using Mechanix

We are particularly interested in how tangible design work might be captured in a way that facilitates sharing with and reconstruction by others. Similar to how sample code may guide novice programmers, well-documented examples of tangible work may enable children to find inspiration from and learn through the construction of others' designs. Furthermore, because students' interactions with tangible toolkits are difficult to capture in project-based learning environments, tools for logging interactions may be especially useful for researchers in the learning sciences [7]. This need serves as the inspiration for Mechanix, an interactive system for the construction and documentation of mechanical engineering system designs.

Mechanix consists of a set of tangible simple machine components that users arranged on a large, vertical interactive display to guide a physical marble through various challenges. By actively

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configuring the tangible components, children explore fundamental physics principles such as gravity, momentum, and inertia while investigating engineering considerations such as precision and uncertainty. A rear-mounted image-detection system captures the spatial arrangement of the tangible components, collecting them in a library of user-generated examples. These examples may be referenced by subsequent children as they create their own solutions to the same challenges.

This paper focuses on the outcomes of studies we have conducted with children using Mechanix. In particular, we examine the unique affordances provided by the system for documenting tangible design work, facilitating social learning and collaboration, and introducing young children to physics concepts and engineering systems design. The results of our studies may be of particular interest to interaction designers developing tangible toolkits for children in the domains of physics and engineering.

2. LEARNING THEORY

Mechanix is motivated by prior research in the learning sciences and in interaction design for children. The foundational work of Piaget [27], Papert [25, 26], and Vygotsky [40] informs our general approach to learning, which emphasizes project-based learning, collaboration, and manipulatives as "objects to think with" [25]. Research on example-based learning further supports the incorporation of user-generated examples to guide and inspire children as they engage in the design of compound systems.

2.1 Constructionism

Constructivists remind us that learning occurs as individuals actively engage in sensemaking based on their experiences in the world [1]. Constructionist theorists argue that this process is enhanced when the learner is actively involved in the creation of a personally-meaningful object that can be displayed, shared, and discussed [25]. By constructing, testing, and redesigning these personal artifacts, children engage in a process of transformative inquiry that refines and solidifies their understanding of abstract concepts [1, 26]. Furthermore, construction activities encourage "epistemological pluralism," supporting both bricolage strategies involving the continual negotiation with and rearrangement of materials as well as more axiomatic or structured design approaches [38].

2.2 Socio-Constructivism

Socio-Constructivism suggests that knowledge is constructed through socially mediated interactions. Vygotsky argued that interaction with a more experienced peer can help a novice learner transcend his own personal cognitive capabilities [40]. Although this theory is traditionally applied to collocated synchronous interactions, the advent of Internet-enabled learning venues has demonstrated the applicability of social-constructivist principles to the design of asynchronous virtual learning environments [9].

2.3 Example-Based Learning

Example-based learning can be especially helpful for guiding novices, particularly when problems are paired with worked examples [3]. In the context of design, examples serve as sources of inspiration and as references that a designer may use to incorporate relevant features into their own work [8, 17, 30]. The quantity of generated ideas increases as designers are exposed to examples, and unfamiliar examples can help designers avoid "design fixation," or the tendency to repeat familiar elements in their own designs [30].

3. RELATED WORK

Mechanix builds on prior work in physics simulation software, tangible interfaces, and interactive surfaces.

3.1 Physics Simulation Software

Physics simulation software provides a dynamic and engaging format for developing problem solving and design thinking strategies. ASSIST is an interactive-whiteboard-based system that employs pen input and sketch recognition to enable users to quickly draw and test mechanical systems [2]. With games such as The Incredible Machine, children create Rube-Goldberg systems to solve challenges [36]. These software-only solutions offer the benefits of being relatively low-cost and allowing users to explore an extensive library of virtual objects.

However, for children in elementary school transitioning into the concrete operational stage of development [28], tangible interfaces offer several advantages over purely on-screen interactions. In a comparison of tangible and graphical interfaces in a museum environment, Horn demonstrated that children, particularly girls, were significantly more likely to try out a tangible interface over a graphical one [18]. Additional studies have demonstrated the potential of tangible interfaces to better facilitate collaboration, increase engagement, and appeal to children's well-documented familiarity and dexterity with physical objects [14, 29, 41].

3.2 Manipulatives

Physical manipulatives are common in elementary school classrooms and have been utilized for decades to facilitate and enhance learning [23, 10, 31]. Computationally-enhanced manipulatives such as the Cricket [32], Curlybot [15], and SystemBlocks [42] have been shown to make abstract ideas such as feedback and control more transparent for children. Furthermore, tangible construction toolkits present issues typical of engineering design that are absent from purely virtual systems such as precision, energy loss, friction, and uncertainty. Direct experience with these factors increases students' understanding of the target domain [6]. Although existing tangible toolkits offer numerous affordances, they do not provide built-in support for learning from others' examples or for constructing new designs. Instead, support is provided externally through online communities such as forums. A construction kit that encourages collaborative learning by automatically documenting expert work may be particularly helpful for guiding novices.

3.3 Interactive Surfaces

Interactive surfaces have become increasingly popular tools for supporting collaborative design work. Commercial tabletops such as the Microsoft Surface [22] and SMART Table [35] utilize horizontal touch screens to enable multi-user collaboration. Many researchers have enhanced virtual touch-table interaction with tangibles. Examples range from Urp, an early tabletop surface with tangibles used for urban planning [39] to Lumino, a system that enables users to build in three-dimensions with tangibles on an interactive tabletop [4]. Techniques such as diffuse illumination and frustrated total internal reflection are commonly used for multi-touch surfaces but require infrared lights and diffuser material on top of an infrared camera and a projector. As a result, these implementations may be beyond the budget of typical educational environments.

Although tabletop surfaces have been relatively popular, vertical interactive surfaces afford the benefits of increased visibility and support for larger groups, as they allow users to share a common viewpoint [33]. Furthermore, vertical surfaces enable interactions influenced by the force of gravity, which is not possible with horizontal displays. Techniques for vertically-oriented interactive surfaces include resistive touch screens (e.g. SMART board [35]), infrared and ultrasonic sensors, computer imaging (e.g. Collaborage [24]), and RFID tags (e.g. Senseboard [20]). Similar to tabletop surfaces, many of these implementations require significant, specialized hardware for each tangible piece.

Prior work indicates the potential for a low-cost, interactive display for young children to explore physics concepts through a gravity-based tangible interface. Furthermore, there are opportunities to incorporate example-based learning using an automated documentation system.

4. MECHANIX

Mechanix is a system for children to build, test, explore, and share engineering systems designs. With Mechanix, children combine and configure tangible simple machines on a vertical magnetic display to guide a physical marble between two points. Successful designs may be saved into a library of user-generated examples which can be accessed by subsequent children seeking assistance or inspiration in their own design process [37].

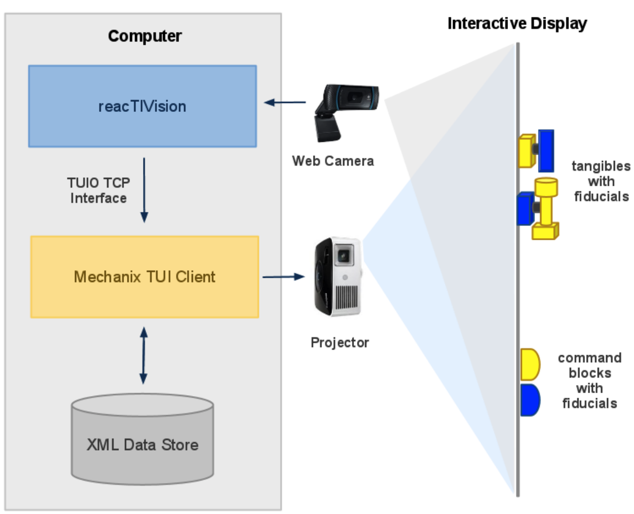


Figure 2: Mechanix system overview

With Mechanix, we were deliberate in designing a low-cost system that would be readily accessible to most educational institutions. Mechanix is instrumented with a set of acrylic tangible magnetic components, a low-cost LED projector, a standard web camera, a laptop computer, and an inexpensive wire-mesh and acrylic display. Each simple machine component is marked by a unique fiducial image, allowing its location and orientation to be recorded via ReacTIVision, an open-source image recognition engine [21]. A custom Java-based client was developed to process the ReacTIVision events, manage the library of user-generated content in an XML data store, and project the interactive visual content onto the screen. This constitutes significantly fewer resources than analogous museum-based exhibits employing large and costly touch surfaces [19].

4.1 Interaction Design

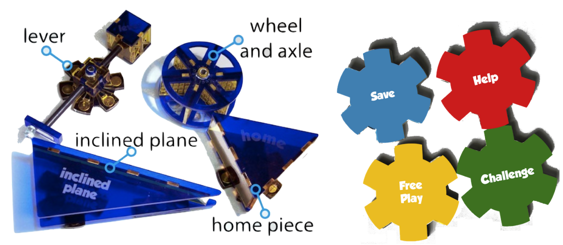
Mechanix was designed to simultaneously support exploration of simple machines components in a gravity-based system, multiuser collaboration, seamless recording of user designs, and unobstructed projection of virtual content. This combination of design considerations necessitated the development of a novel interactive display for the Mechanix system.

4.1.1 Interactive Display

The Mechanix interactive display is a large (2' x 3') vertical, semi-transparent, magnetic surface composed of steel mesh, projection paper, and clear acrylic. Its large size and vertical orientation is intended to facilitate synchronous collaboration and co-construction among multiple users. The steel mesh allows for the magnetic front-attachment of simple machine components in a system utilizing gravity while providing sufficient transparency to perform image tracking and project visual content from behind the surface. This arrangement allows children to interact with the system without disrupting the underlying image recognition and projection of virtual content.

4.1.2 Tangible Components

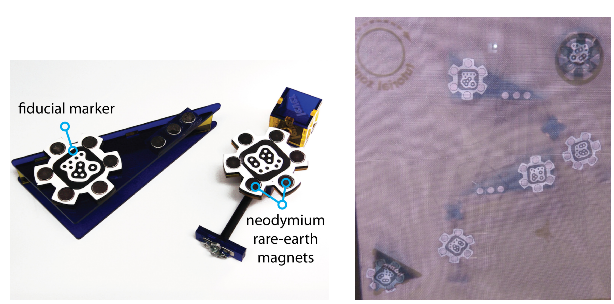
The Mechanix tangible toolkit consists of two types of tangibles: simple machines and command pieces.



(a) Simple machines (b) Command pieces

Figure 3: Mechanix pieces

The available simple machines include inclined planes, levers, wheel & axles, and a home piece (Figure 3a). The center of gravity of the lever can be altered by adjusting a configurable set of weights on its base, which changes the direction of rotation. Each piece is labeled with its name etched clearly on the front. Command pieces are used to access play modes, save designs, and view the designs of others (Figure 3b). Challenges and designs are revealed by rotating the appropriate command piece on the display and are selected by removing the command piece from the surface.



(a) Fiducial markers (b) Rear view of display

Figure 4: Fiducial markers on components

The back of each tangible piece is equipped with high-strength neodymium magnets for attaching to the display and a distinct fiducial image for image tracking (Figure 4a). This design enables children to interact directly with the tangible components while their designs are seamlessly recorded into the library of solutions.

4.1.3 Interaction Modes

The virtual content of the Mechanix system provides access to the library of user-generated solutions and the two modes of interaction: *Free Play* and *Challenge*. The evolution of these interaction modes is described in our User Studies section.

(a) *Free Play* Mode (b) *Challenge* Mode

Figure 5: Modes of interaction

Free Play provides a blank canvas for children to design configurations of simple machines to guide a physical marble between two points (Figure 5a). Pieces may be placed anywhere except where a "monster" icon is randomly projected, which provides a design constraint. Successful designs may be saved as a new challenge in the user library and consist of only the start, end, and "monster" pieces. The design itself is recorded as the first solution to that challenge.

In *Challenge* mode, users cycle through peer-generated challenges by rotating the corresponding command piece. These challenges, which consist of a start and an end (or "home") piece, are projected onto the screen (Figure 5b). The child aligns the corresponding simple machine pieces with their projections and then proceeds to arrange intervening pieces to guide the marble from start to end. By dictating the placement of the start and end pieces, the *Challenge* mode presents a more constrained activity than *Free Play*.

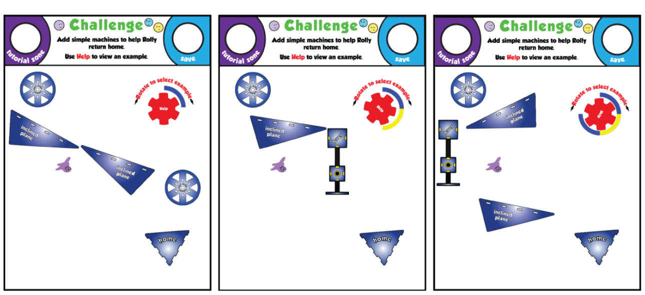


Figure 6: Cycling through solutions for a challenge

Successful designs may be saved to the library, and subsequent users can cycle through saved solutions using the "Help" command piece (Figure 6). Images of solutions are projected onto the display, allowing the user to align the corresponding tangible pieces in order to test the design. Viewing multiple solutions helps children appreciate the myriad ways simple machines can be combined to accomplish the same task.

Further scaffolding is provided by the Tutorial Zone, a designated section of the screen where children can place a simple machine piece to activate an animated tutorial describing its formal properties (Figure 7).

Figure 7: Tutorial content for the Wheel & Axle

5. USER STUDIES

Employing a Design-Based Research methodology [12], we engaged in three exploratory studies to examine various affordances of the Mechanix system over the course of its development. The first was a preliminary study to discover key parameters that impact children's engagement with the system. The second study examined the system's capability to support multi-user collaboration and introduce physics and engineering concepts. Finally, the third study reviewed children's use of examples in the process of building and testing engineering designs.

In each study, we used a grounded-theory approach [16], employed top-down verbal analysis [11] and microgenetic methods [34] for data analysis, and utilized open-ended post-tests and field observations. All children who participated in the studies were recruited from a California neighborhood mailing list. The children tested were between the ages of 5 and 11, which was selected as an appropriate range for children transitioning from the preoperational to concrete stages of development. Each session was video recorded with two cameras and microphones for transcription and analysis. In our transcripts, extraneous or repeated words such as "like" have been removed for readability.

5.1 Preliminary Usability Study

5.1.1 Methodology

The purpose of the preliminary usability study was to observe children's interactions with the system and to identify areas for further research. Two girls, ages 7 and 9, were tested individually in thirty-minute sessions. Accompanying parents were invited to work alongside their child.

During the usability study, children had the freedom to choose and switch between two different modes: *Make a Challenge* and *Take a Challenge*. The *Take a Challenge* mode was the precursor to the current *Challenge* mode and had essentially the same functionality. The *Make a Challenge* mode was the precursor to the current *Free Play* mode and was originally designed for expert users to create challenges for others to solve.

5.1.2 Results

Our preliminary study revealed several insights that helped determine the direction of our subsequent investigations.

1) Uncovering user preferences

Each child exhibited distinct preferences for the separate modes of the Mechanix interface. One child preferred the *Make a Challenge* mode and spent the entire session creating her own designs while the other remained in the *Take a Challenge* mode for the duration of the study. The ability to select a mode of interaction appeared to be valuable for supporting each child's design strategies and preferences.

2) Repurposing of *Make a Challenge*

The child who engaged in the *Make a Challenge* mode used the mode in a way we had not intended. Instead of designing challenges for other users to solve, which would consist of only a start and an end piece, the child used the mode as a blank slate to create her own complete designs. The mode became a means to quickly experiment with the simple machine pieces and uncover their properties without the constraints of the *Take a Challenge* mode. This result suggested a need for an exploratory entry point, which became the new purpose of the *Make a Challenge* mode. This mode was later renamed *Free Play* to encourage exploration of simple machines with fewer constraints.

3) Documentation for exploration

We discovered that children may utilize documentation as a means of exploring their own work. When one child came across her own saved design, she declared that the configuration looked "cool" and wanted to recreate it. It was only when her mother pointed out that it was her own design that the child recognized her work. This result led us to consider the use of documentation as a means for children to review and reflect on their own designs in addition to testing and exploring other children's work. The child's reaction to viewing her own design affirmed that documenting design work can be personally meaningful, highlighting a unique affordance of the Mechanix system.

4) Viewing examples

Finally, neither of the children chose to view examples during their session, preferring to explore the system by making their own designs. At the end of the sessions, each child was shown the library of solutions, and each successfully selected and tested an example from the library. Although both children appeared to find value in looking at the examples, they also expressed a preference for playing on their own. For example, when asked if she would prefer to look through an example or create a design, one child said, "I kind of like just playing with it."

The results of the preliminary study suggest that children may prefer to design on their own before exploring the work of others. Differences in preferences for modes of play encouraged us to study whether initial use with a specific interaction mode might affect design outcomes such as quantity or quality of designs. Finally, we saw that children and their parents were able to work collaboratively to design systems, and we became interested in how children might work with each other. These results informed the design of our following user study.

5.2 User Study 1: Collaboration & Learning

5.2.1 Methodology

Building upon the insights gained in our initial usability study, we engaged in a followup study to evaluate the collaboration affordances and potential learning outcomes of Mechanix. Specifically, our objectives were to 1) evaluate whether children exhibit an increased understanding of simple machines and engineering systems design after using the system, 2) investigate whether the initial mode of interaction (*Make a Challenge* or *Take A Challenge*) impacts design outcomes in a post-test, and 3) assess the potential for Mechanix to support both synchronous and asynchronous interactions in the process of creating designs and solutions.

We invited children to engage in thirty-minute sessions with Mechanix as individuals or in groups of two. Thirteen child volunteers, all first-time users between the ages of 5 and 11 (5 female, 8 male), participated in the study. Three of the children engaged with the system individually while two pairs of siblings and three pairs of friends engaged in groups of two. At the start of each session, the children were asked if they had formal knowledge of simple machines, and ten of the thirteen responded that they had none. As part of our assessment of the collaboration affordances of Mechanix, we did not inhibit parents who accompanied their children from offering guidance or enforcing turn-taking procedures during the study.

Individuals and pairs were randomly assigned to either the *Design A Solution* group or the *Create a Design* group. These modes were roughly equivalent to the prior *Take a Challenge* and *Make a Challenge* modes with the nomenclature having been adjusted to suggest different objectives. Children in the former group were asked to continuously solve any of four challenges, each one consisting of projected start and end pieces with a randomly-placed monster. Students in the latter group were asked to create as many simple machine configurations as they liked on the blank canvas, being careful to avoid projected monsters. After 15 minutes, all children were given the same post-test of designing as many different solutions as they could for a single novel challenge configuration. Following the post-test, children were asked several questions about their experience using the system.

5.2.2 Results

Our results verified several key affordances of Mechanix and identified areas for further research.

1) Learning about simple machines and engineering design

Each of our users demonstrated increased understandings of simple machines. For all but three, this included developing a nomenclature to describe the individual pieces, which emerged from reading and verbalizing the inscribed names on the simple machine components. Furthermore, our participants demonstrated increased understanding of the physical properties of the pieces. This was manifested in their growing ability to describe the behaviors of isolated components and configure them in more complex systems. Within the time allotted, however, none of the children learned to adjust the weights on the levers to bias the spin direction, although one eleven year-old participant, the oldest in the study, indicated that he understood that the weights were contributing to the behavior. He was able to formalize his understanding only after the researchers directed him to the lever tutorial.

2) Design outcomes as a function of interaction modes

Although we attempted to examine differences in design outcomes as a function of initial interaction modes, we found that limitations in the design of our study prevented us from drawing any significant conclusions. The study did not adequately account for preexisting strategies to allow for confidence in attributing outcome differences solely to the interaction mode. Furthermore, design quality (which could be measured in several ways such as the average number of pieces in a design or the use of more complex pieces like the lever) does not necessarily correlate with quantity of designs. Still, differences in strategies for creating designs were noted between children who interacted with each mode. Children who used *Create A Design* were more likely to experiment with alternative pieces, rapidly switch out problematic pieces, and move them with broader gestures. Those who engaged with *Design a Solution* were more likely to attempt repeated small adjustments to finalize their designs.

3) Support for synchronous and asynchronous interactions

At 2' x 3', the Mechanix vertical display readily supported synchronous collaboration between two users. For individual children, this was manifested in the ability of their parents to observe and provide assistance from several feet away. For example, one nine year-old, after experimenting exclusively with inclined planes and the wheel & axle, was encouraged by his mother to experiment with the lever, which he later used successfully. Each of the two sibling groups were advised to commence with egalitarian turn-taking, but reverted to a stage where one would attempt to wrest control from the other. The groups of friends were also encouraged to take turns, but they each quickly advanced to employ simultaneous, positive collaborative strategies. These collaborations were made possible not only by the large, vertical display but by the existence of multiple points of interaction with the system, with each simple machine component providing the potential for concurrent adjustment. Systems created by children working together were some of the more complex and imaginative designs, confirmming the importance of this key affordance of Mechanix.

Only four participants were in a position to engage in asynchronous learning by exploring the library of examples. Our first participant was initially reluctant to view examples, but when he finally decided to view one, he suddenly became aware of the existence of levers in the toolkit. At the end of his session he confirmed this by saying, "earlier I wasn't using the levers at all. I was just using the circle and the inclined planes. But then I think that I learned that levers could be just as useful, if not more useful, than the other ones." Similarly, a sibling group declined to view solutions early on, but after struggling to solve a challenge for six minutes, they agreed to look at an alternative approach. The children were then successful in viewing and configuring the design they chose from the library. These results were consistent with our previous observation that although children recognize the benefit of examples, they are reluctant to view them. It is possible that children may require an extended period of interaction with Mechanix in order to fully take advantage of the library of solutions. Given these results, the impact of examples on learning outcomes and design strategies became the focus of our third user study.

5.3 User Study 2: The Impact of Examples

5.3.1 Methodology

In the last of our three studies, we evaluated the impact of viewing examples on design strategies and learning outcomes. Three children between the ages of 7 and 9 (1 female, 2 male) were invited to engage individually in hour-long sessions with Mechanix. Before commencing, each child was asked if they had any formal knowledge of simple machines, and all three responded that they had none.

Each session commenced with a brief tutorial of the system followed by a period in the *Free Play* mode in which the children explored by creating their own designs. Subsequently, the children were presented with three successive challenges consisting of different start and end pieces. After solving each challenge, the participants were directed to view a set of three solutions, select their favorite, and test the example. Upon completing each example, children were asked why they selected a particular example and what they thought of testing it.

After finishing the three challenges, the children were presented with a test of creating as many solutions to a particular challenge as possible within the allotted time. The session concluded with a period of self-directed use in which the child could elect to engage in either the *Challenge* or *Free Play* mode and switch freely between the two. At the end of the study, each child was interviewed using a semi-structured protocol in which the researchers asked questions specific to the child's experience viewing and testing the examples.

5.3.2 Results

Each of our three participants exhibited distinct benefits from and attitudes toward user-generated examples. These may be categorized as 1) conscious recognition of the value of examples, 2) unrecognized application of learning through examples, and 3) use of examples to reflect on one's own design process. To protect the children's identity, the masculine gender will be used to describe each child. In the figures, dark lines indicate the top of a component.

1) Conscious recognition of the value of examples for inspiration and discovery

One participant demonstrated a conscious appreciation for the provided examples, particularly for their potential to reveal ways to combine the simple machines and explore the functionality of more advanced pieces. After solving the first challenge with a single piece, the child decided to test a complex example (Figure 8):

> *Participant 1*: I'm going to do the hardest one.
> *Researcher*: Why did you pick that one?
> *Participant 1*: Because I liked it more, I liked it.
> *Researcher*: What did you like about it?
> *Participant 1*: That it used these two, cause I can't use them (points to wheel & axles). I can, but it's hard for me.

In this exchange, the child acknowledged that the example served as an opportunity to confidently explore the use of a piece that he found difficult to master. For the second challenge, the participant again selected an example that involved pieces that interested him:

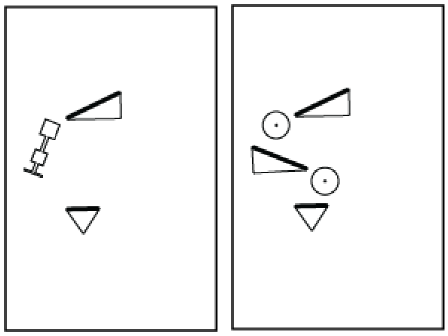


Figure 8: Participant 1's solution to a challenge and the child's selected example to the same challenge

> *Researcher*: So why did you pick that example?
> *Participant 1*: Because I like to use these (points to lever). And this (points to wheel & axle). I like how it moves. And when it drops (rotates lever), it seems like it's going to fall, but it actually doesn't.
> *Researcher*: Oh, what does it do?
> *Participant 1*: You think it's going to go like that (rotates lever 200° to the bottom left), but it goes like that (rotates lever 100° to the bottom right).

Here, the child demonstrated that exploring the example caused him to challenge and reconsider assumptions about the functionality of the lever component. Yet, despite this child's enthusiasm for examples, he did not elect to view them during the ten minutes of unstructured play at the end of the session. When asked why this was the case, the child responded that he had already learned from the examples during the study and that given the opportunity to look at more solutions, he would not.

2) Unrecognized application of learning through examples

Another participant exhibited an unrecognized benefit to viewing examples:

> *Participant 2*: (looking at an example) I don't think that will work.
> (the child ends up trying this example)
> *Researcher*: Do you want to tell us why you picked that example?
> *Participant 2*: I thought it would work if I would have put this (lever) here like that, but it wouldn't have worked. So I thought it would be better if I could move it like this (angles the lever) closer so it would be resting on here and would work like (demos) that. Cause it would face this way, into there (home).

Simply by testing an example, the participant transformed his conception of possible successful configurations. Whereas he initially believed that the example was faulty, his successful implementation of the example caused him to view the lever piece in a renewed light. Upon subsequent consideration, he not only believed that the example would work but that he always thought it would. Still, during our post hoc querying, he indicated that although the examples could be used to gain ideas for solving a challenge, he did not find them particularly instructive, indicating a lack of awareness of the benefit he appeared to derive from the process.

3) Use of examples to reflect on one's own design process

The remaining participant, the oldest in the study, immediately demonstrated a more advanced understanding of how to combine and operate the pieces than the other two children. In fact, some of this child's designs during the initial free play involved more complex arrangements than those provided in the examples (Figure 9).

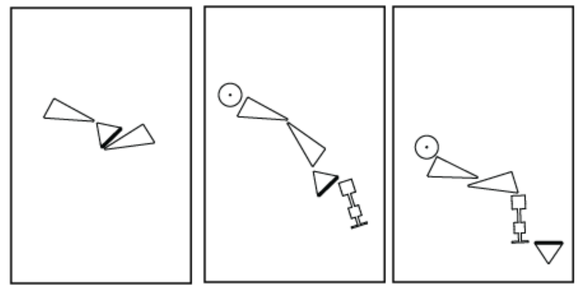


Figure 9: Participant 3's initial *Free Play* designs

During our post-interview, the child indicated, not unexpectedly, that although the examples revealed different ways to solve each challenge, he did not find value in viewing them:

> *Researcher*: If you had a choice, if we weren't telling you, do you think you would look at the solutions?
> *Participant 3*: No.
> *Researcher*: There would be no reason for you to ever look at them?
> *Participant 3*: There would not be any reason to look at them.
> *Researcher*: Why is that?
> *Participant 3*: Because I don't need them.

However, during the time allocated for unstructured play at the end of the study, he spontaneously began looking through a set of examples that happened to be his own solutions to the post test challenge:

> *Participant 3*: I'm going to look through all the examples (begins looking through his own solutions) ...Wait, I made this one? Oh yeah...cool!

Similar to the user in our initial study, this participant enjoyed viewing his own creations. What might have been lost as ephemeral designs (as evidenced by the fact that he initially did not recognize them as his own) became "objects to think with," admire, reflect upon, and evaluate at a later point in time.

These results suggest that access to examples in the Mechanix system may provide various benefits to children depending on their needs, preferences, and levels of self-awareness. For less confident and inexperienced children, viewing examples may provide inspiration for exploring simple machine configurations beyond their current conceptions. By simply testing these examples, our participants demonstrated immediate benefits in terms of understanding how pieces interact with one another and in their ability to evaluate the potential success of a configuration via visual inspection. Furthermore, experienced users may benefit from reviewing, reflecting upon, and admiring their own solutions. Still, only one of our three participants voluntarily elected to view examples, and all of them verbally suggested that they would be unlikely to view solutions if unprompted. This result suggests that children prefer to explore and develop their own solutions. It seems that our current design for viewing examples may not mesh well with this preference, regardless of the benefits children consciously or unconsciously derive from viewing and testing the examples.

6. DISCUSSION

Our three user studies enabled us to examine the unique affordances that Mechanix provides for children to explore physics principles and engineering systems design. In all three studies, children exhibited evidence of learning about simple machines by developing a vocabulary for the pieces and utilizing the pieces in isolation and in progressively complex combinations. Learning was facilitated through synchronous collaboration as parents often provided instructional support and encouragement to try out new pieces, and siblings and peers worked together to solve challenges. These interactions were made possible by Mechanix's large vertical display and multiple tangible components.

We found that our library of user-generated solutions positively impacted design strategies and learning outcomes for our participants, albeit differently with respect to their needs, preferences, and levels of self-awareness. First, they served as an opportunity to aid children when they were unable to solve a challenge or wished to learn how to use a particular piece. Second, the examples served as inspiration for learning new strategies for successfully combining pieces in a design. Finally, for some children, the library served as a means of self-reflection, enabling them to review and admire their own work.

Despite these benefits, the children only viewed examples when explicitly asked to do so. Although several children realized the utility of testing examples, they still preferred to design on their own. There are a few possible implications of this result: the system should allow for initial free-form exploration, children may require more time with the system before they become interested in viewing the work of others, and a passive system in which children must actively elect to view examples may not utilize the full potential of Mechanix's affordances.

Finally, we observed that children were highly engaged when using Mechanix. Participants often exhibited signs of flow when interacting with the system [13]: they worked uninterrupted for long periods of time, sometimes extending beyond ten minutes, as they attempted to configure the pieces to solve particularly difficult challenges. Children's engagement with Mechanix suggests that engineering design and the physical properties of simple machines can be made approachable to young audiences through appropriately-designed tangible interfaces, automated documentation tools, and computational supports.

7. CONCLUSIONS & FUTURE WORK

Through a series of progressive studies of children using Mechanix, we have examined and uncovered affordances of the system for documenting tangible design work, facilitating social learning and collaboration, providing distinct entry points that appeal to a broad range of learners, and introducing young children to physics concepts and engineering systems design. More specifically, these studies indicated that (1) the vertical display and multiple points of interaction afforded by the tangible components enabled children to engage in collaborative design, and (2) the documentation of tangible design work provided several benefits to children, including exposing them to different approaches to combining simple machine pieces, enabling them to experiment with unfamiliar pieces, and serving as a portfolio with which children can review their own designs.

The studies exposed several opportunities for enhancing the design of the system while revealing issues meriting further exploration. One area of study that requires additional refinement is assessing the impact of interaction modes on design outcomes. Critical to this process will be the development of novel metrics for assessing the quality of designs and experimental procedures for isolating the impact of the interaction mode on design strategies.

Another feature that deserves significant exploration is the proper framing of user-generated examples. Our studies suggest that multiple avenues for interacting with examples are warranted to support diverse users. Potential improvements include supporting personalization for saved designs to inspire production and exploration of examples as well as compelling visualizations to assist children in comparing their own designs with a range of other examples. In addition, examples might be seamlessly incorporated through real-time recommendations in response to user interactions.

Additional affordances are currently being developed. Networking features are being integrated to support extensive shared user libraries as well as synchronous design collaborations between distributed systems. Real-time image tracking might be employed to create a visual log of user interactions to encourage reflection on personal design strategies as well as post hoc assessment by researchers.

By integrating example-based learning and automated documentation into the design process, Mechanix contributes new insights into how these features may engage children in exploring and learning about physics and engineering design.

8. REFERENCES

[1] E. Ackermann. Piaget's Constructivism, Papert's Constructionism: What's the Difference? http://learning.media.mit.edu/content/publications/EA.Piaget%20_%20Papert.pdf, 2001.

[2] C. Alvarado and R. Davis. Resolving ambiguities to create a natural sketch based interface. In *Proc. of IJCAI*, 2001.

[3] R. Atkinson, S. Derry, A. Renki, and D. Wortham. Learning from examples: Instructional principles from the worked examples research. *Review of Educational Research*, 70:181–214, 2000.

[4] P. Baudisch, T. Becker, , and F. Rudeck. Lumino: Tangible building blocks based on glass fiber bundles. In *Proc. CHI '10*, pages 1165–1174, 2010.

[5] M. Bers. *Blocks, robots and computers: Learning about technology in early childhood.* New York: Teacher's College Press, 2008.

[6] P. Blikstein and U. Wilensky. Bifocal modeling: A framework for combining computer modeling, robotics and real-world sensing. Annual meeting of the American Research Education Association, 2007.

[7] P. Blikstein and M. Worsley. Learning analytics: Assessing constructionist learning using machine learning. Annual meeting of the American Research Education Association, 2011.

[8] N. Bonnardel. Creativity in design activities: The role of analogies in a constrained cognitive environment. In *Proc. Creativity Cognition*, pages 158–165, 1999.

[9] A. Borthick, J. D.R., and S. Wakai. Designing learning experiences within Learner's Zones of Proximal Development (ZPDs): Enabling collaborative learning on-site and online. *Journal of information sciences*, 17(1):107–134, 2003.

[10] N. Brosterman and K. Togashi. *Inventing Kindergarten*. H.N. Abrahms, 1997.

[11] M. T. H. Chi. Quantifying qualitative analyses of verbal data: A practical guide. *g qualitative analyses of verbal data: A practical guide. Journal of the Learning Sciences*, 6(3):271–315, 1997.

[12] P. Cobb, J. Confrey, A. A. diSessa, R. Lehrer, and L. Schauble. Design experiments in educational research. *Educational Researcher*, 32(1):9–13, 2003.

[13] M. Csikszentmihalyi. *Optimal experience: Psychological studies of flow in consciousness.* Cambridge University Press, 1998.

[14] Y. Fernaeus and J. Tholander. Looking at the computer but doing it on land: Children's interactions in a tangible programming space. In *Proc. of CHI '08*, pages 3–18. ACM Press, 2008.

[15] P. Frei, V. Su, B. Mikhak, and H. Ishii. Curlybot: Designing a new class of computational toys. In *Proc. of CHI '00*, pages 129–136. ACM Press, 2000.

[16] B. G. Glaser and A. Strauss. *The Discovery of grounded theory: Strategies for qualitative research.* Chicago: Adline Publishing, 1967.

[17] S. Herring, C. Chang, J. Krantzler, and B. Bailey. Getting inspired!: Understanding how and why examples are used in creative design practice. In *Proc. of CHI '09*, page 87Ð89. ACM Press, 2008.

[18] M. Horn, E. Solovey, R. Crouser, and R. Jacob. Comparing the use of tangible and graphical programming languages for informal science education. In *Proc. of CHI '09*, pages 975–984. ACM Press, 2009.

[19] E. Hornecker. "I don't understand it either, but it is cool" - Visitor Interactions with a Multi-Touch Table in a Museum. In *Proc. of IEEE Tabletop*, 2008.

[20] R. Jacob, I. Hiroshi, G. Pangaro, and J. Patten. A tangible interface for organizing information using a grid. In *Proc. of CHI '02*, pages 339–346. ACM Press, 2002.

[21] M. Kaltenbrunner and R. Benica. reacTIVision: A computer-vision framework for table-based tangible interaction. In *Proc. of TEI '07*, Baton Rouge, Lousiana, 2007.

[22] Microsoft. http://www.microsoft.com/surface/en/us/default.aspx.

[23] M. Montessori and H. Holmes. *The Montessori Method*. Frederick A. Stokes, 1912.

[24] T. Moran, E. Saund, W. Melle, K. Gujar, A. Fishkin, and B. Harrison. Design and technology for collaborage: Collaborative collages of information on physical walls. In *Proc. UIST '99*, pages 197–206. ACM Press, 1999.

[25] S. Papert. Situating constructionism. In S. Papert and I. Harel, editors, *Constructionism*. Cambridge, MA: MIT Press, 1991.

[26] S. Papert. *The Children's Machine: Rethinking School in the Age of the Computer*. New York: BasicBooks, 1993.

[27] J. Piaget. *The Origins of Intelligence in Children.* New York, NY: International University Press, 1952.

[28] J. Piaget. The stages of the intellectual development of the child. *Bull Menninger Clin*, 26:120–128, 1962.

[29] S. Price, Y. Rogers, M. Scaife, D. Stanton, and H. Neale. Using 'tangibles' to promote novel forms of playful learning. In *Proc. of Interacting with Computers '03*, pages 169–185. ACM Press, 2003.

[30] A. Purcell and J. Gero. The effects of examples on the results of a design activity. *Knowledge-Based Systems Journal*, 5(1):82–91, 1992.

[31] M. Resnick, F. Martin, R. Berg, R. Borovoy, V. Colella, K. Kramer, and B. Silverman. Digital manipulatives: New toys to think with. In *Proc. of CHI '98*. ACM Press, 1998.

[32] M. Resnick, F. Martin, R. Sargent, and B. Silverman. Programmable bricks: Toys to think with. *IBM Systems Journal*, 35(3-4):443–452, 1996.

[33] Y. Rogers and S. Lindley. Collaborating around vertical and horizontal large interactive displays: Which way is best? *Interacting with Computers*, 16:1133– 1152, 2004.

[34] A. H. Schoenfeld, P. Smith, J., and A. Arcavi. Learning: The microgenetic analysis of one student's evolving understanding of a complex subject matter domain. In R. Glaser, editor, *Advances in instructional psychology*, pages 55–175. Hillsdale, NJ: Lawrence Erlbaum Associates., 1991.

[35] SMART. http://smarttech.com/us/Solutions/Education+Solutions/Products+for+education/Interactive+whiteboards+and+displays/SMART+Board+interactive+whiteboards.

[36] The Incredible Machine. http://en.wikipedia.org/wiki/The_Incredible_Machine_(game).

[37] T. Tseng, C. Bryant, and P. Blikstein. Mechanix: An interactive display for exploring engineering design through a tangible interface. In *Proc. of TEI '11*, 2011.

[38] S. Turkle and S. Papert. Epistemological pluralism and the revaluation of the concrete. *Journal of Mathematical Behavior*, 11(1):3–33, 1993.

[39] J. Underkoffler and H. Ishii. Urp: A luminous-tangible workbench for urban planning and design. In *Proc. of CHI 1999*, 1999.

[40] L. Vygotsky. *Mind in society: The development of higher psychological processes*. Harvard University Press, 1978.

[41] L. Xie, A. Antle, and N. Motademi. Are tangibles more fun?: Comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. In *Proc. of TEI '08*. ACM Press, 2008.

[42] O. Zuckerman, S. Arida, and M. Resnick. Extending tangible interfaces for education: Digital montessori-inspired manipulatives. In *Proc. of CHI '05*. ACM Press, 2005.