Prototyping and Simulating Complex Systems with Paper Craft and Augmented Reality: An Initial Investigation

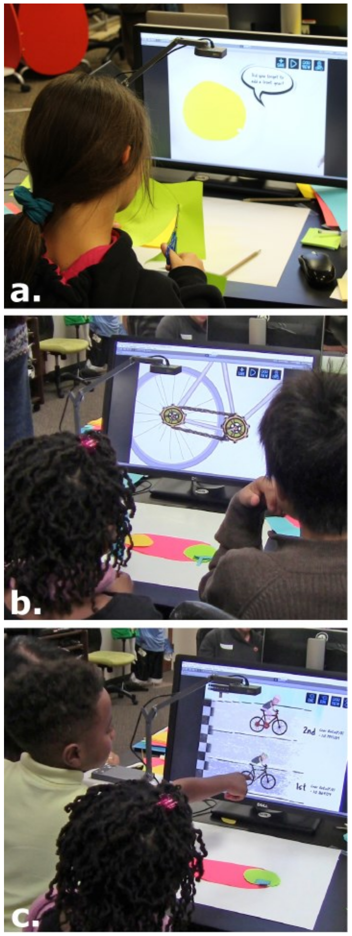

Figure 1: With *Rainbow,* children **(a)** make lo-fi prototypes of complex systems (*e.g.,* bike gears), **(b)** which are digitized into virtual models, and **(c)** tested in a digital simulation environment. See supplementary video for a demonstration.

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TEI '18, March 18–21, 2018, Stockholm, Sweden

ACM ISBN 978-1-4503-5568-1/18/03.
https://doi.org/10.1145/3173225.3173264

Abstract
We present early work developing an Augmented Reality (AR) system that allows young children to design and experiment with complex systems (*e.g.,* bicycle gears, human circulatory system). Our novel approach combines low-fidelity prototyping to help children represent creative ideas, AR visualization to scaffold iterative design, and virtual simulation to support personalized experiments. To evaluate our approach, we conducted an exploratory study with eight children (ages 8-11) using an initial prototype. Our findings demonstrate the viability of our approach, uncover usability challenges, and suggest opportunities for future work. We also distill additional design implications from a follow-up participatory design session with children.

Author Keywords
Augmented reality; prototyping; simulation; children

Introduction
With advances in computer vision, increases in the performance and availability of GPUs, and new, emerging platforms such as *HoloLens* [25] and *ARKit* [1], there is renewed interest in the role of Augmented Reality (AR) in learning (*e.g.,* [17,38]). While there is

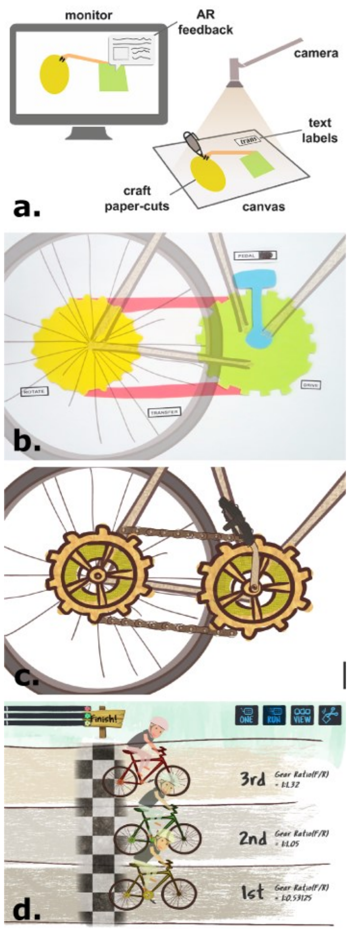

Figure 2: (a) An overview of *Rainbow.* **(b)** An example paper prototype of the bike gear system as visualized in the AR environment; **(c)** the resulting virtual models; and **(d)** a bike race simulation to test the gears.

rich literature exploring how AR may support learning and *in situ* training dating back to the early 2000s—*e.g.,* by providing contextual information via head-mounted displays [21,22] or by mobile devices [7,20]—this work is primarily aimed at adults [14,37] or high school students [7,8,28,30]. In our research, we are interested in developing and exploring new AR systems for younger learners, grades K-5, who are still developing cognitively, socially, and emotionally, and who draw primarily on direct physical and social experiences to construct understanding [39].

In this paper, we introduce *Rainbow,* an AR-based "smart desk" that allows children to rapidly prototype complex systems using paper and then to test their designs in an accompanying digital simulation environment (Figure 1). As a child builds a prototype, *Rainbow* actively analyzes the work surface using computer vision to provide *in-situ* computer-mediated scaffolds. The scaffolds provide timely feedback and bridge connections to existing knowledge to help the child solve problems that otherwise might be too difficult [29]. Because the testing environment is digital, there is tremendous flexibility in how a design can be simulated and used for scientific inquiry (*e.g.,* by dynamically changing experimental variables, modifying the testing context).

Our work is informed by the pedagogical theories of *Constructionism* [19,27] and the *Learning by Design* framework [5]—both which emphasize that learning is enhanced when children construct physical artifacts and collaboratively reflect on and share their work. To support this constructive learning experience, our work focuses on providing a creative design interface—which can be shared by multiple users—to facilitate collaborative design, rapid prototyping, and prompt evaluation of ideas.

Below, we provide background on AR-based learning systems, outline the current *Rainbow* prototype, and describe a preliminary evaluation. Our primary contributions include the initial design and implementation of *Rainbow*, key findings drawn from our user study, and a distillation of future work informed by a follow-up participatory design session.

Related Work

While many Augmented Reality (AR) systems have been developed to support interactive design tasks [2,9,24,36] and simulation-based experiments [8,21,30], there is little work targeting young children who are still developing their understanding of the world and often struggle to grasp abstract concepts (*e.g.,* cause-and-effect) [11]. Prior work has demonstrated the educational potential of AR simulation in various subjects, including physics [21,22], electronics [18,30], and science literacy [7]. For example, *Augmented Chemistry* [8] helps learners understand and explore molecular structures via AR-enhanced tangible manipulations. While *Rainbow* also augments low-fidelity materials with digital representations, we engage the user in the entire design process—from ideating and prototyping to testing and analysis. Moreover, we scaffold the user through computer-mediated prompts to bridge knowledge gaps and address design problems.

Lo-fi prototyping using paper, sketches, or wireframes can be useful for quick iteration of design and engineering ideas at a minimal cost [3]. Lo-fi materials, which require less time and design skills, are

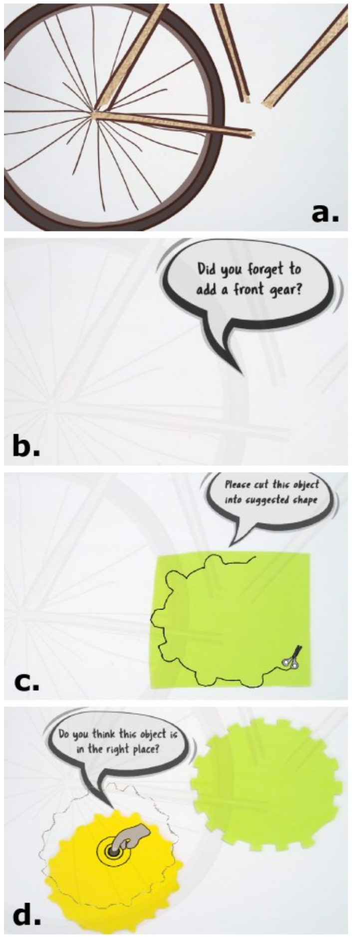

Figure 3: (a) Augmentation of a design prompt; suggestive feedback indicates **(b)** a missing object, **(c)** an inappropriate shape, and **(d)** a wrong position.

particularly suitable for young children to give tangible form to their creative ideas [6,15,31]. Many interactive prototyping systems employ tangible lo-fi materials to support the creation of virtual 3D models and 3D-printable mock ups. For example, *DuploTrack* [16] and Miller et al.'s work [26] use Lego building blocks to construct 3D models with the help of visual guidance. *Maker's Marks* [32] and *KidCad* [10] take advantage of sculpting materials to rapidly build 3D-printable mockups and reconstruct physical models, respectively. Also, paper and sketches have been used for editing 3D CAD models [33] and designing living spaces [23]. However, there is little work aimed at helping young children design and understand complex systems, which is our goal. In addition, *Rainbow* uses a novel lo-fi prototyping interface to represent physical structures, program objects' functions, and specify logical connections (Figure 2b).

System Design

Rainbow is designed to facilitate creative prototyping of systems, scaffold learning during the design process, and engage young children in personalized scientific inquiry. Our initial implementation offers a table design workspace in which user can interact with both physical materials and an AR visualization. The system is comprised of a canvas to construct prototypes with lo-fi materials (*e.g.,* craft paper, scissors, markers), a top-down document camera to recognize the prototype, and a monitor to display AR visualizations and the simulation environment (Figure 2). We describe three major parts of our approach: (1) prototyping with the lo-fi design interface; (2) design assessment and AR feedback for scaffolding; (3) functional simulation to support testing and scientific inquiry (Figure 2). See the supplementary video for a demonstration.

Lo-fi prototyping interface

The lo-fi prototyping interface leverages the tangibility and flexibility of craft material in order to engage young children in rapid prototyping of ideas. It encourages externalizing creative ideas into concrete representations that can be refined through iterations. Our initial implementation supports paper prototyping. The prototyping interface allows the child to specify common features needed to build a system, which includes the *structure*, *function*, and *logical connections* [12,13,34]. We describe each below.

Designing *Structure*. The initial AR canvas shows a design prompt (*e.g.,* "create your own bicycle gears"). An accompanying background image is superimposed on the canvas to help children think about the layout and position of system components (Figure 3). Users create each component object by choosing a color paper and cutting it into a shape—the color of paper determines the object type (*e.g., yellow* for a front gear). Then, users place the objects on the canvas, aligning them with the AR image.

Designing *Function**.* Users specify the primary behavior of each *structure* by naming it (*e.g., rotate* for a wheel object) and describing related variables (*e.g.,* rotational speed for the rotate behavior). The user selects a behavior from a provided deck of printed text labels and places it near the corresponding object on the canvas. Then, the system augments the label with a caption illustrating the definition and how to describe its function variable values (Figure 4a, 4c). The user can specify a numerical value by filling a horizontal level bar (Figure 4b) or select a categorical value by marking a check box on the label (Figure 4d).

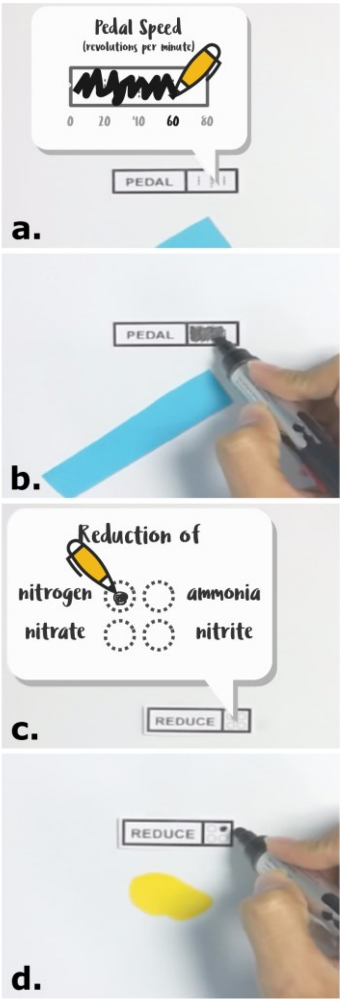

Figure 4: (a, b) Numerical function variable design; **(c, d)** categorical function variable design.

Designing *Logical Connections*. Users describe the relationship between *structure* components and behaviors such as cause-and-effect, synchronization, and parallelism. Our current implementation does not yet support designing these logical connections.

Automatic machine assessment and scaffolding
Repeatedly throughout the prototyping process, the machine assesses the validity of the prototype and provides contextualized feedback. The physical prototype is first translated into a computational model by computer vision techniques. The parallel processing of the image captured by the camera—including filtering, color clustering, blob analysis, text recognition, and variable recognition—generates a computational model of structures, behaviors, and logical connections in the prototype. Then, the system evaluates the model by comparing it to the standard model and identifies potential problems (*e.g.,* an object is placed in the wrong position). In the end, the AR renderer visualizes feedback that can help resolve identified problems (Figure 3b-d). The visualization includes both textual and graphical messages tailored to suggest corrective actions. For example, if an object is too far from its desirable position, the AR feedback shows a message (*e.g.,* "*Do you think this object is in the right place?*") and an animation moving it toward the correct position (Figure 3d).

Functional simulation
Key to any design activity is the ability to test and iterate on one's design. Functional simulation offers personalized inquiry activities in which children can test their designs, learn from these tests, and update their designs accordingly. The simulation supports learning about the functional mechanisms but also serves as a design prompt motivating iterations on prototypes. Once the user selects a set of previously built prototypes to compare (Figure 5b), the visualization converts each prototype into a virtual model that represents the design variables of the prototype. The final simulation is designed to highlight the functional difference across the virtual models through animated visualizations, possibly making it easier for children to make observations about the relationship between a specific design variable and functional phenomena. More importantly, it presents details of functional parameters (*e.g.,* a gear ratio of a bike gear prototype) to support in-depth analysis of the results (Figure 5c).

Preliminary Study
To gain a preliminary understanding of how children interact with Rainbow and future design ideas, we conducted a two-session participatory design study with eight children (ages 8-11). The study was part of a Collaborative Inquiry [6] design program in which children collaborate with adult researchers to design and develop technologies for children's learning and play. The participants were split into three groups of 2-3 children along with adult partners who captured and analyzed the children's interactions and ideas.

The first session was designed to evaluate the usability of our Rainbow prototype, which included: (i) a 15-minute overview of our prototype; (ii) 40 minutes of prototyping a bicycle gear system and reporting likes, dislikes, and design ideas [35]; (iii) 20 minutes of answering usability questions; and (iv) the adult partners' observation debrief. We used a reduced version of Rainbow with one design prompt—building bike gears—that supported designing structures but not

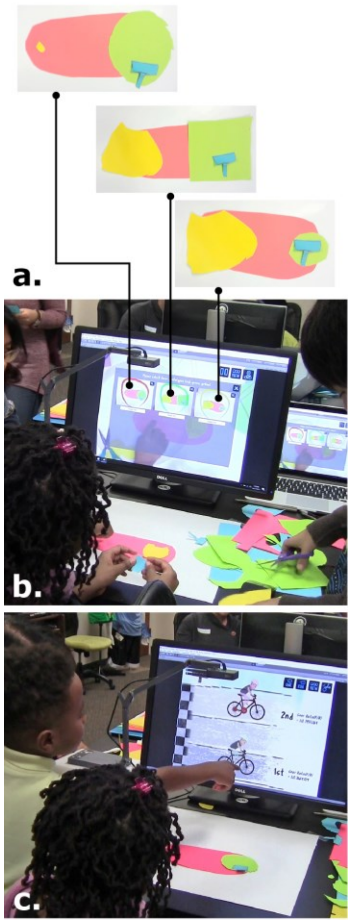

Figure 5: Children experiment with **(a, b)** previously built prototypes and **(c)** observe differences in their functions.

functions or logical connections (these were set automatically by the system).

In the second design session, children did not use Rainbow but, instead, engaged in lo-fi prototyping activities to help brainstorm future directions. The session started with a 15-minute overview of the design activity in which children chose sample systems to design (*e.g.,* a camera lens system). Then, children were divided into three groups and engaged in a 45-minute lo-fi prototyping activity. In the end, children presented their design ideas along with the prototypes.

Data and analysis

We collected system log including images of children's prototypes, a written summary of design ideas [6,15], the adult partners' reflections, and audio/video recordings of the entire activity. We used a mixed deductive and inductive approach, following Chi's eight-step process [4], to validate our approach, understand children's interaction, and identify future design ideas. Two researchers developed the initial themes including reported user experience, observed usability issues, and emerging interaction ideas. Key findings were verified by reviewing qualitative (*e.g.,* quotes) and quantitative (*e.g.,* the number of logged design iterations) data. We present our findings below.

Findings

Creation, testing and simulating. Overall, children learned how to use Rainbow and liked the core features such as the use of craft (*e.g.,* "*making our own shapes*"), responsive augmentation (*e.g.,* "*the gears mirror the paper size*"), and personalized simulation (*e.g.,* "*we can race our gears*") (Figure 1). From the beginning, children built creative designs with unexpected shapes and layouts using the lo-fi interface. Then children rapidly iterated on their prototypes, making use of testing and suggestions shown in the AR scaffolding feedback. The system log shows that each group iterated on prototypes an average of 17 times during the 40-minute activity. Children created a variety of designs with different characteristics (*e.g.,* different gear ratios), which they tested with simulated experiments. For example, a group simulated three bike prototypes of high-, mid-, and low-gear ratios and reported, "*the yellow [rear gear] is so small and it still won*" (Figure 5).

Challenges. Though children appreciated the usefulness of the suggestive feedback (*e.g.,* a child stated "*Yes it was helpful …[to] tell you where to move it*"), some complained about the sensitivity of machine assessment (*e.g.,* "*It was picky*"). Children struggled at the beginning to understand what they were supposed to do and the extent of Rainbow's functionality (*e.g., "No idea what to do*" and "*[did not know] we could choose our own gears*"). We also observed tension between promoting creativity in prototypes and controlling variables in experimentation. To test a hypothesis, all design variables (*e.g.,* chain and pedal) need to be controlled with the exception of an independent variable (*e.g.,* gears). However, children occasionally changed multiple aspects of a prototype at a time (*e.g.,* comparing two gear prototypes that differ in both gear sizes and pedal sizes), which complicated the experimental setup and subsequent analysis. A child noticed the problem, stating, "*if you are trying to prove something … then you want to keep your variable the same … science class taught me that*."

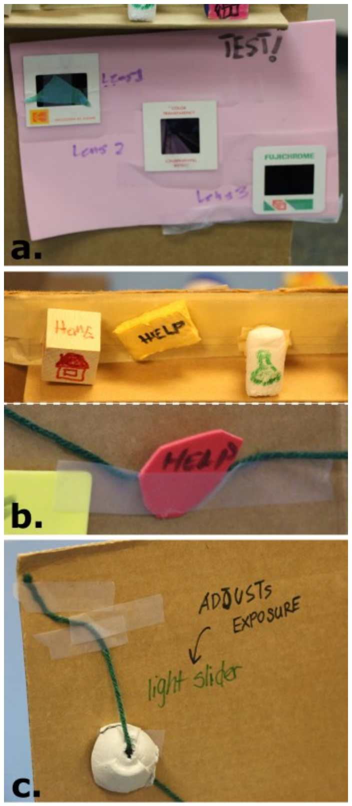

Figure 6: Children suggested design ideas of **(a)** including a simulation panel to test their prototypes while designing, **(b)** help buttons to receive scaffolding feedback as needed, and **(c)** a tangible slider to control a numerical variable.

Design ideas. From the two design sessions, we were able to distill key design ideas related to scaffolding, the lo-fi prototyping interface, and the use of AR. First, children preferred testing their own designs *first* before receiving suggestive feedback. They stressed the importance of having control over *when* to open a scaffolding or "hint" dialogue (Figure 6b). Second, children came up with novel design features for future systems, including one group who designed an intelligent doll attached a speech function to the prototype that the doll could tell about itself (*e.g.,* "*Once built, he can talk to you [to help you design]*"). Another group designed a camera system that included a tangible slider control to manipulate a hidden property (*e.g.,* the exposure value of a lens, Figure 6c). Lastly, two groups shared an idea of using immersive technologies (*e.g.,* VR goggles) rather than an external display. A child stated, "*VR is more fun. Looking in the computer, you can get more distracted but, in the VR, you can just focus on one entire thing*."

Discussion and Conclusion

We presented early research on combining lo-fi prototyping and AR visualization to promote a new model of computer-mediated learning. Children learn through making physical prototypes, receive feedback from machine intelligence, and conduct personalized experiments with virtual simulation.

While our initial work demonstrates the viability of our approach, revealed usability issues, and offered insights into future work, our evaluation was limited to examining high-level user experience and soliciting design ideas. We did not examine how technical problems could arise from children's unexpected design activities (*e.g.,* when one child created a very tiny object to represent a gear, the computer vision algorithm simply recognizes this as noise).

In our future work, we plan to: (i) expand Rainbow to accommodate a broader range of lo-fi materials; (ii) implement improved scaffolds that better direct scientific experiments and are not seen as intrusive; (iii) develop multiple example applications in other domains (*e.g.,* biology or ecology); (iv) employ AR technologies such as a projected display or AR goggles to promote new forms of interaction; and (v) conduct expanded user studies in a range of learning contexts (*e.g.,* classrooms or afterschool programs).

Acknowledgements

We thank the children and researchers in the Kidsteam program at the University of Maryland, College Park. This work was supported by an NSF Grant IIS-441184.

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