

LightUp: An augmented learning platform for electronics

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ABSTRACT

We present and evaluate the design of LightUp, an augmented learning platform for electronics. LightUp helps children explore engineering and electronics by foregrounding fundamental concepts and backgrounding the extraneous intricacies of circuit construction. LightUp consists of electronic components (e.g. wire, bulb, motor, microcontroller) mounted on blocks that connect to each other magnetically to form circuits. In addition, LightUp provides an “informational lens” through a mobile app that recognizes the components in a photographed circuit and augments the image with visualizations of otherwise invisible circuit behavior. Our study findings demonstrate the experiential learning made possible by augmenting an intuitive circuit-building platform with information that allows children to learn skills that will help them develop engineering skills and agency.

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

General Terms

Design, Experimentation

Keywords

Tangible interfaces, constructionism, education, electronics

1. INTRODUCTION

Electronics permeate the fabric of modern society; on our desks, in our pockets, and by every street corner. Children were once able to open up everyday consumer electronics to figure out how things worked, which has helped countless children learn about powerful ideas in engineering, mathematics, system dynamics, and complex systems in a tangible constructionist fashion. As devices have shrunk over the decades it has become much harder to learn by taking apart and repurposing consumer electronics.

Educational toolkits have been recently developed to address this issue, but a gap remains between kits designed to be low-threshold (easily accessible to novices) and high-ceiling (useful for later prototyping and experimentation) [1]. LightUp serves to fill this void by providing a platform that facilitates circuit construction while foregrounding the fundamental concepts that will help children develop transferable knowledge for later projects. LightUp consists of modular blocks that connect

magnetically to form electronic circuits (Figure 1). The first iteration of LightUp [2] has been successfully tested in small user studies, where valuable feedback was collected. We have iterated through several major redesigns informed by extensive observational research and a controlled study. In this paper we describe the overall design of the LightUp platform, including a novel system for nonpolar magnetic connections that encourages rapid iteration when building circuits, and an augmented reality system that provides an informational lens to help children understand and simulate the physics of circuits in real time.



Figure 1. Children using LightUp

2. RELATED WORK

Some electronic construction kits strive to create functional modules and introduce a much simpler abstraction layer on top of circuit construction, effectively backgrounding much of the physics of circuits. Such kits directly extend Papert’s ideas about the design of computer languages and interfaces for children [3,4] into the electronics realm. Papert famously compared the Logo computer language (built from the ground up to be easily learnable by children, as well as a powerful expressive medium) to the BASIC language, which was built with unnecessary technical complexities limiting its reach and power.

littleBits [5] and Lego Mindstorms¹ apply this to electronics by providing an abstraction over circuit construction and focusing on higher level concepts. For example, littleBits consists of electronic modules that all connect linearly with 3 contacts and Lego Mindstorms uses Lego bricks with 2 metal contacts. In both cases, basic issues such as polarity and validation of connections are taken care of by the platform—users cannot connect two blocks in the “wrong” way. This approach enables novices to become engaged with electronics quickly through prior interest in other disciplines, such as art or robotics, and without any training in

¹ <http://mindstorms.lego.com>

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electronics. However, because such toolkits are designed to hide circuit construction, the skills are not easily transferable to interacting with conventional DIY electronics, such as microcontroller boards (Arduino², Basic Stamp³, GoGo Board [3], HandyBoard [6]) or conventional electronic components which sometimes do have inherent polarity.

On the other end of the spectrum are kits that use traditional electronics, but centralize the most used functions onto a microcontroller system. Such platforms work well with modules within their ecosystem and provide the greatest transferability of skills, but have a steeper learning curve when interfacing with conventional hardware. For example, when wiring resistors and LEDs to an Arduino board, users need to use breadboards and commercial components without a "design layer" that might make their use more intuitive and age-appropriate.

In the middle of the spectrum are kits that expose electronic circuitry while simplifying circuit construction through the use of easier connection mechanisms and information printed on electronic blocks. For example, SnapCircuits⁴ uses button snaps for connections. Maintaining a close resemblance to a conventional circuit makes skills more easily transferrable to DIY electronics while making the kit more accessible. However, compromises in the connection mechanism can also introduce complications. For example, connections in SnapCircuits introduce vertical layers in the circuit that need to be kept in mind when building large circuits. In addition, these kits must strike a delicate balance between providing enough information on each block to facilitate understanding, while not intimidating users with excessive technical jargon. Without a way to reveal information in a timely manner, children are still left with a difficult transition to conventional DIY electronics.

To provide a more guided approach, other systems allow people to interact with conventional electronic components on a touch table to guide interaction. Conradi's system [7] allows users to place components on the table surface and outlines their connection points and behavior. Users can virtually connect the devices to see visualizations of behavior and then connect the actual circuits on the surface. Such systems greatly facilitate interaction with conventional hardware and provide just-in-time learning, but can be expensive or difficult to deploy.

Based on a literature review and analysis of previous work, we designed LightUp to increase engagement, maximize transferability of skills, and allow for widespread adoption by adopting these design principles: transparency, schematic duality, rapid iteration, instant feedback, informational lens, and low cost.

3. DESIGN

Standard electronic components were never designed for ease of manipulation or learnability, but rather with cost and size constraints in mind. In contrast, we have designed LightUp to maximize transparency, ease of reconfiguration, and learning. LightUp blocks connect magnetically in any direction, so circuits can be built by simply moving blocks next to each other. The component and wire blocks are sized on a standard grid, so completed circuits resemble the neat layout of a circuit diagram. Each block is labeled with the name and schematic symbol of the component. The components provided range from resistors, capacitors, and wires to transistors, integrated circuits, and

microcontrollers, allowing for both simple and complex circuits. LightUp is engineered so that accidental connections are unlikely to damage components or harm the user. The blocks are labeled with TopCodes [8], open source optical markers that allow a computer vision system to recognize the configuration of the circuit and augment the physical circuit with information about invisible behavior such as current flow and voltage.

Following the tenets of Design-Based Research [9], we conducted several observational and controlled studies with children of varying ages to test the LightUp platform and iteratively improve its design. We observed and recorded the interactions of children aged 6-16 with LightUp in two informal environments. The first was at Hack the Future, a workshop environment where children were free to walk around to various programming and electronics-related stations. The second was at Stanford SPLAH, a weekend event where we taught two classes on digital logic to middle school students using both LightUp and more conventional circuit-building material.

Our third and more comprehensive user study was a controlled experiment with 12 high school students (6 males and 6 females) from a diverse school in the US. For this study, we designed several tasks ("build this schematic," "fix this circuit," etc.) and gave students a limited amount of time to solve them. Half of the students used materials commonly used in schools for these tasks (alligator clips, conductive tape, wires, discrete components) and half used LightUp. We measured how much time they spent, analyzed the nature and frequency of their errors, and took field notes about their utterances during construction.

These three studies, taken together, allowed us to isolate and test different design decisions, and assess ways to make user interactions with LightUp more intuitive, engaging, and educational. For space considerations, we will not be able to describe the full dataset, and will focus instead on describing each of our design implementations and illustrate its effectiveness with data from the studies.

3.1 Transparency

One key design decision was to maintain a clear connection between the blocks and the electronic components. The components are mounted on plastic using custom-designed printed circuit boards. All LightUp blocks visually expose the component they encapsulate (Figure 2), making it easier for users to make the transition to conventional components.

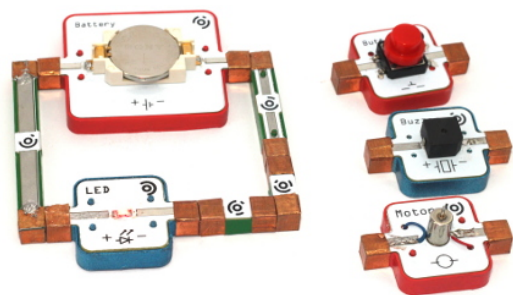


Figure 2. LightUp blocks

Except when safety necessitates extra circuitry, each block encapsulates a single component to ensure that the full functionality of each device is accessible to the user. The connections from the blocks' terminals to the component are highlighted so users can see how LightUp connections are nothing more than an ease-of-use improvement for standard circuit

² <http://www.arduino.cc>

³ <http://www.parallax.com/tabid/295/default.aspx>

⁴ www.snapcircuits.net

construction. Each block also features the component name and symbol making it easy to identify. Schematic Duality

Circuits built with LightUp closely resemble schematic diagrams. This seamlessly introduces an important aspect of sharing and collaborating on circuits. Users can build and modify existing designs without having to go through the additional step of translating the schematic to breadboard connections or tracing a jumble of alligator clips. In fact, during our controlled study, we frequently observed children in the control group (who used conventional materials) reorganizing a jumble of alligator clips into a rectilinear fashion when debugging or explaining their circuit. Many times, this step introduces errors into the circuit because of shorting or loose connections. While a breadboard offers a similarly organized alternative, it obscures a large part of the circuit (users cannot see inside the breadboard). In addition, many concepts in electrical engineering become more visible when a circuit is laid out as a schematic. For example, the idea of series and parallel configurations is much easier to observe when a circuit is laid out as a schematic.

LightUp inherently encourages a close resemblance between physical circuits and schematic diagrams with its design, which we call “schematic duality”. The components are all sized to have their terminals on a grid. Wire blocks are only provided in increments of this grid size to ensure that connections always are lined up. Furthermore, by making the contact points fit together at 90-degree angles, circuits are much more likely to be built in a rectilinear fashion that resembles a schematic. In our studies, we found that the majority of children using LightUp built their initial circuits in a rectilinear fashion. However, sometimes when modifications or additions to their circuit were made, they no longer follow this paradigm. We found that children enjoyed building circuits in creative and unusual shapes such as circles or even 3D structures. Given these unexpected findings from our studies, we plan on eventually offering two modes of construction, one using a metallic base grid to enforce regularity, and a free-form mode for personal explorations.

3.2 Rapid Iteration

Rapid iteration in programming encourages users to experiment frequently and discover concepts on their own [10]. For circuit building, traditional equipment such as breadboards discourages iteration since connections are hard to make, track, and visualize. LightUp brings the benefits of rapid iteration to hardware by providing a platform that enables circuits to be reconfigured quickly. Freely rotating magnets allow LightUp blocks to snap together in any direction, unlike other construction platforms that use polar connections. In addition, rectilinear circuits make connections and paths readily identifiable when debugging. Because of the low barrier to reconfiguring a circuit, users are more comfortable making alterations to test their mental models of electrical engineering concepts.

To evaluate the usefulness of rapid iteration for learning, we conducted a controlled study in which we examined whether children were able to understand that LEDs are polar elements (light only when connected in one orientation) after interacting with LightUp circuits, or with circuits made with alligator clips. Study subjects were presented with two circuits. The first circuit consisted of an LED correctly connected so it glowed. The second circuit consisted of an incorrectly connected LED, which did not glow. We asked the subjects reconfigure the systems and try to figure out the cause for the visible difference. Half the subjects were given circuits built with LightUp and half were given circuits built with alligator clips (Figure 5). We then asked the

subjects to perform the same task using the other construction system.

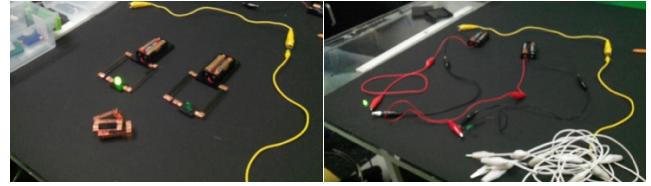


Figure 3. Identical circuits built with LightUp/alligator clips

With LightUp, students were able to discern the important polarity difference between the lit and non-lit LED circuits more quickly and consistently. In the comparison group, students who were able to reconfigure the alligator clip circuit to make the non-lit LED light up had more misconceptions. For example, one student thought that minor details such as the exact position of the alligator clips (e.g. one lying on top or another) made the difference, and another didn’t even realize she had flipped the LED while unclipping and clipping it back. These misconceptions may be minor for a novice, but could compound and cause problems later as these students delve into more complicated circuits and projects. We also tested whether asymmetric pieces and color-coded terminals would facilitate discovery and found that color-coded terminals were more effective than asymmetry on its own. We plan to explore this feature more in future designs.

3.3 Instant Feedback

With LightUp, components and subcircuits begin functioning as soon as they are connected. Thus, users see the effects of their creations progressively throughout the building process. Because of this, users are able to start with a simple circuit and incrementally add more complex behaviors. The incremental building process makes LightUp approachable for users with a wide range of background knowledge. In addition, because users can see the effects of each subcircuit as it is constructed, they can adapt their mental models one at a time throughout the process rather than trying to assimilate the entire behavior at once.

In addition to the feedback provided by the components themselves, LightUp supplements complex devices with embedded debugging information. For example, digital blocks have specially-designed LEDs at each input and output terminal so users can immediately see how signals are progressing in their circuit during construction. We configured the LEDs to turn on whenever a logical “high” signal is passing through them. In our digital blocks (a binary counter and decoder), this proved to be quite effective in helping novices understand how to go between the binary and decimal number systems. Participants at Hack the Future were able to see the binary sequence propagating through the LEDs on each input and output pin, and how that was decoded into hexadecimal notation on the 7-segment display (Figure 4).

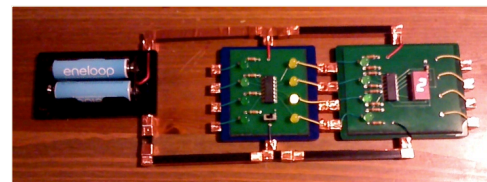


Figure 4. Binary counter and decoder

3.4 Informational Lens

Many aspects of electronics, such as current, voltage, and power dissipation are not directly visible to the user. Having to infer this

information from theory or constantly detach and reattach measurement equipment discourages early learners from recording the properties in detail. In addition, with conventional circuit building, users rarely see the properties of the circuit as a whole and only observe the properties at specific points. To overcome these issues in engineering, professionals use simulation to compute these properties. However, most simulation tools are far too inaccessible to novices. Those that are accessible still contain a separation between the physical and the simulated.

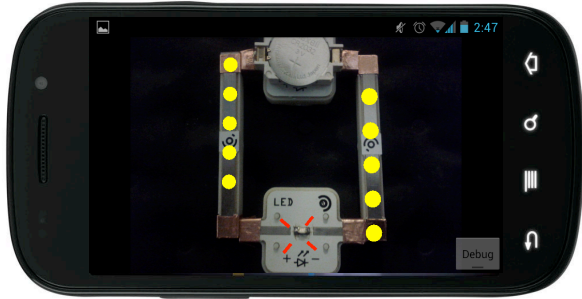


Figure 5. Informational lens showing electron flow

To bridge that gap, LightUp includes a mobile app, inspired by Bifocal Modeling [11], which serves as an augmented reality informational lens with which to view circuits. During typical interaction, users take a picture of a LightUp circuit using the app. Using computer vision markers (TopCodes) on the blocks, the app recognizes the components and connections, builds a digital model, and simulates the circuit using ngSpice⁵, a widely used open source circuit simulator. The results of the simulation are parsed by the app and overlaid onto the actual image of the circuit (Figure 3). Users thus have a representation of the invisible behavior of the circuit, enabling deeper understanding of important concepts in electronics.

3.5 Low Cost

To facilitate its use in schools, LightUp is designed to be low cost and locally producible. The current system uses standard, easily available components, circuit boards, magnets and plastic sheets. The microcontrollers used in LightUp are the PIC16F505 and the Arduino-compatible ATtiny 84, two of the lowest cost microcontrollers available. Furthermore, the informational lens is designed to provide an augmented workspace experience using relatively low cost and easily deployable low-end smartphones and tablets (often available for <\$100) rather than more expensive and unwieldy touch table or projector-based systems.

In addition, LightUp can be locally produced with standard fabrication lab equipment. As laser cutters, CNC machines, and 3D printers become more prevalent in educational settings, it is feasible that students and teachers themselves could make their own LightUp blocks. While we are exploring avenues to mass produce blocks that will be ready out of the box, compatible blocks will always be able to be made with a laser cutter, soldering iron, epoxy, and copper tape.

4. CONCLUSION

LightUp provides an augmented learning platform for electronics, and is able to grow with users as they gain new knowledge and skills. LightUp's focus on transparency and duality with conventional circuits increases the transferability of skills to later

DIY projects. LightUp augments the physical construction kit with an informational lens that makes invisible phenomena visible through a mobile app. Through our studies, we found that enabling both free-form and guided modes of interaction on the same platform could make LightUp more engaging and plan on incorporating our findings into future designs.

5. ACKNOWLEDGMENTS

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⁵ www.ngspice.org