Electronic Popables: exploring paper-based computing through an interactive pop-up book

Jie Qi
Department of Mechanical Engineering
Columbia University
Jq2152@columbia.edu

Advisor: Leah Buechley
High-Low Tech
MIT Media Lab
leah@media.mit.edu

ABSTRACT

We have developed an interactive pop-up book called Electronic Popables to explore paper-based computing. Our book integrates traditional pop-up mechanisms with thin, flexible, paper-based electronics and the result is an artifact that looks and functions much like an ordinary pop-up, but has added elements of dynamic interactivity. This paper introduces the book and, through it, a library of paper-based sensors and a suite of paper-electronics construction techniques. We also reflect on the unique and under-explored opportunities that arise from combining material experimentation, artistic design, and engineering.

Author Keywords

Paper computing, pop-up book, paper-crafts, paper electronics, conductive paint.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

It seems increasingly plausible that electronic books or "e-books"—digital versions of traditional paper books—will someday replace printed books. The content of an e-book is identical to that of a printed one even if the experience of reading in one medium differs from the other, and the devices on which e-books are read, like the Kindle and the Sony Reader, are growing more popular as they become lighter, cheaper, and easier to use and get better mimicking at least some of the qualities of paper.

However, it is hard to imagine reading a pop-up book on a Kindle. Pop-ups are intrinsically three-dimensional and physically interactive, inviting users to pull tabs and levers and open flaps while figures and settings literally jump out of the page. But while it would be difficult—perhaps impossible—to replicate a pop-up onscreen, the physical books present compelling canvases for embedded computing. Precisely the quail ties that make them unlikely candidates for virtual reproduction—their three-dimensionality and mechanical interactivity—make them ideal for computational and electronic augmentation: Volvelles (rotating paper wheels) and folds can be electronically activated with motors and shape memory materials. Tabs, flaps, and volvelles can be employed as sensors and switches, and flat paper surfaces can come alive with dynamic light, color, and sound.

Figure 1. A page from our book depicting the New York City skyline. A bend sensor—the flap in the shape of a boat in the foreground—controls the lights in the skyscrapers.

This paper introduces a pop-up book we constructed to explore these possibilities. The book, a page of which is shown in Figure 1, extends our earlier work in (flat) paper computing. In our previous work we employed conductive paints, magnetic paints and magnets to build a construction kit for paper-based computing [7]. Here we use our kit in conjunction with new materials like piezo resistive elastomers, resistive paints, and shape memory alloys. We strive to blend electronics invisibly with paper, creating components like switches, sensors, and electro-mechanical actuators out of pop-up mechanisms and keeping circuitry

CHI 2009, April 4–9, 2009, Boston, Massachusetts, USA.

as thin and flexible as possible. In the course of constructing the book, we also began to compile an electronic-pop-up-mechanism library, and developed several general-purpose techniques for combining electronics and paper.

RELATED WORK: PAPER AND COMPUTERS

The most familiar paper-computer relationship occurs through printers. Printers have become so commonplace in our lives that they are taken for granted, but simple printers present rich, under-explored possibilities for integrations of computation and paper. For example, the HyperGami and Pop-up Workshop applications use printers to explore computational design for paper sculptures [10,12]. HyperGami allows users to generate and manipulate three-dimensional shapes by writing Scheme programs. Folding nets for these shapes are generated by the software and printed onto paper. Then, users can cut out the nets and fold them into colorful polyhedral sculptures [10]. Similarly, Pop-up Workshop enables users to design pop-up pages which are then printed on color printers and assembled by hand [12].

A different kind of ingenious printing—where machine-readable codes are printed onto paper—has given rise to technologies like Anoto [1], in which a pen with a built-in camera uses a barely-perceptible dot pattern printed onto a page to capture its tip's position. The Anoto Pen can thus record and store what someone has written and this data can be downloaded to a computer to be saved, manipulated, or employed by other software. Several user-interface researchers have exploited this type of technology to enable users to employ drawing and writing in computational environments. For example, in early work in this area, Johnson et al. used machine readable forms—like the forms commonly used for standardized tests—as "paper user interfaces" [13]. More recently, Liao et al.'s PapierCraft system, which employs the Anoto, enables users to fluidly edit and annotate paper documents and then upload these manipulations to companion digital pages [15]. Similarly, Tsandilas' et al.'s Musink software, also Anoto based, enables music composers to capture and edit handwritten scores [20].

Another genre of related research involves combining paper with a variety of hardware to build custom user-interfaces. For example, Mackay et al. developed a system that employs a PDA and WACOM tablet [16] to enable biologists to record, evaluate, and enrich their handwritten notes. Raffle et al. also used a WACOM tablet, along with custom built hardware, in the Jabberstamp application, which lets children associate recorded audio with paper drawings [17]. In a different but related vein, Back et al. constructed a paper book augmented with RFID tags and capacitive sensors as part of an immersive museum installation called the Listen Reader [3], and in the Bookisheet project Watanabe et al. attached bend sensors and switches to paper to construct a novel user interface [21]. In the best of these projects, equal attention is paid to paper and computation. The materials compliment each other and the system exploits the affordances of each medium.

Our Popables project differs from most of these projects by focusing on a stand-alone paper book. Almost all of the previous work has treated paper as a user interface component. Though our book could function as a user interface, it was designed to be an independent interactive artifact. Furthermore, our project breaks new ground in exploring the integration of electronics and pop-up mechanisms and in explicitly focusing equal attention on functional and aesthetic design.

MATERIALS AND CONSTRUCTION

We constructed our book by building individual interactive pop-up cards and then assembling them into a book. We were aided in our pop-up construction by examining existing books, like Sabuda's beautiful Alice in Wonderland [19], and following pop-up how-to instructions. We found Barton's *The pop-up page engineer* series [4] and Birmingham's *Pop Up!: A Manual of Paper Mechanisms* [5] especially useful.

Electronics are attached to both sides of our pages. On some pages the majority of the circuitry is hidden on the backside and on others most of the circuitry is incorporated into the decoration on the front. Most pages include a combination of paper-based (flat) circuitry and traditional electronics. We used three primary materials to build our paper-based circuits: copper tape, conductive fabric, and conductive paint.

The copper tape is a highly conductive 100% copper material with an adhesive attached to one side. It can be cut with scissors and attached to paper like traditional tape. To create two-dimensional traces, straight lines of tape are soldered to each other. The tape has the advantages of being flat, highly conductive—with a surface resistivity of < .01 Ohm per square—and easy to solder to, but breaks on repeated bending, and must be applied tape-like in linear sections.

To get around some of these deficiencies, we also employed a tin and copper plated fabric called Zelt [11] in our designs. To attach the fabric to our pages, we applied a heat activated adhesive to one side of the fabric [6]. Though not as conductive as copper tape—with a surface resistivity of < .1 Ohm per square—the fabric can withstand repeated bending, is thinner and softer than the tape, can be cut into curving and large area traces, and can be laser cut.

The most suitable conductor for paper, however is conductive paint. Conductive paint enables a designer to paint or sketch functioning circuitry just the way he would sketch or paint an electrical schematic or a decorative drawing. What's more, the paint is absorbed into the fabric of the paper and thus becomes part of the paper artifact in a way that the tape and fabric do not. We used a watersoluble copper-based paint called CuPro-Cote [11] for this project. Other similar conductors that we experimented with (the silver and nickel print materials from [11] for example) are solvent-based and can be dangerous to employ without respirators, latex gloves, and other protective equipment. The CuPro-Cote can be applied just like a traditional latex paint. It does have drawbacks however. With a surface resistivity of ~1 Ohm per square, it cannot carry large amounts of current without significant voltage drop, and, like other paints, it cracks—and therefore loses conductivity—on repeated bending. In addition to the CuPro-Cote, we also made use of a carbon-based resistive paint called YShield [11]—with a surface resistivity of ~10 Ohms per square—to build paper-based resistors and potentiometers. Figure 2 shows the back of one of our pages that includes several of these materials.

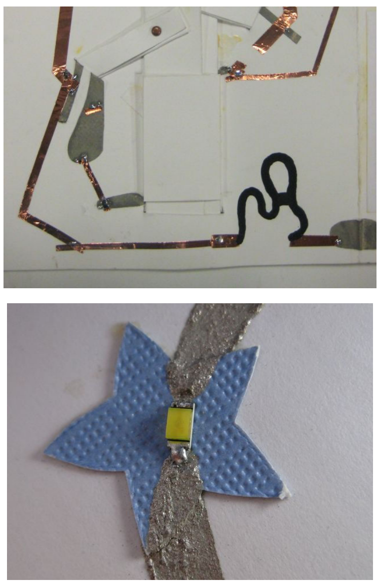

Figure 2. Top: the back of one of our pages that includes conductive fabric (grey), resistive paint (black), and copper tape (orange). Bottom: an LED soldered to a trace painted in CuPro-Cote.

We employed a variety of techniques to attach these materials to each other and to attach electronic elements to our circuitry. Copper tape and conductive fabric were soldered together. To electrically connect a painted trace to another material, we simply extended our painting onto the other material. Electronic elements like Light Emitting Diodes (LEDs) were soldered directly to paint, fabric or tape. Figure 2, for example, shows an LED soldered to a painted trace.

LEDs, circuitry, and other components are embedded directly into individual pages, but a power supply, a custom-made Arduino microcontroller [2], and a speaker are shared by all the pages. These shared components—elements of our construction kit for paper computing [7]—are small stand-alone circuit boards with magnets attached to them. The magnets make physical and electrical connections between the boards and other (ferrous) surfaces. To attach these magnetic boards to our book, we glued pieces of steel-impregnated-paper to each page. This "paper steel" keeps the magnetic components attached to the pages while seamlessly blending into the rest of the paper construction. When not being used by individual pages, the magnetic elements are stored on the first page of the book.

In addition to the materials we have mentioned, we also used shape memory alloys, conductive thread, and piezo resistive elastomers. We will describe these materials in the next section, when we describe their applications.

To assemble our final book, we attached all of our individual cards together in accordion fashion, with blank pages separating the interactive pages to protect and insulate their circuitry. To access the circuitry on the backs of the pages, the book can be extracted from its cover, unfolded, and "read" from the reverse side. Figure 3 shows images of our completed book.

Figure 3. Top, left: the book, right: magnetic electronic modules stored on the first page. Bottom: the book, turned inside-out, showing circuitry on the back of the pages.

THE BOOK: ELECTRONIC POPABLES

Our book consists of six pages, each with a different pop-up theme, different sensor mechanisms, and—in some cases—unique actuator mechanisms. We now turn to an examination of each of our pages and, along the way, introduce a library of paper-based sensors.

Page One: Pink Flowers and Switches

In the first page we constructed we experimented with switches made from pull-tab mechanisms. Pull tabs can generate movement in pop-ups in an endless variety of ways. Our page, shown in Figure 4, employs three mechanisms: levers, slides, and pivots. The page has no computational elements and is powered only by the magnetic battery. As each tab is pulled it closes (or opens) a switch, causing LEDs in the page to turn on or off.

Pulling the first tab (the lever) causes a flower petal to slide upward and the flower underneath it to light up. When a user pulls the second tab (the slide), a bee moves in a waving line down the page, blinking on and off as it travels. The third component is a series of flowers that all rotate and glow when a tab (the pivot) is pulled.

Figure 4. Top: the flower on the left is open and the bee is at the top of its track. Bottom: after pulling the tabs, the flower is closed and the bee is at the bottom of its track, its light turned off.

To make a switches, a pull-tab is constructed out of a tube with conductive fabric applied to its interior, as shown in Figure 5. (All conductive material in our diagrams is shown in yellow.) An insert for the tube contains two ends of an uncompleted circuit from the pop-up page. As the tube's conductive fabric slides across the tube insert it makes contact with the two ends and completes the circuit.

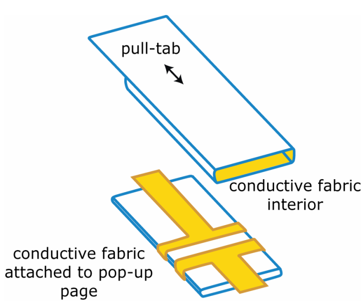

Figure 5. A paper switch mechanism. Note: conductors are shown in yellow in this and all subsequent diagrams.

Page Two: Orange Ocean and Potentiometers

Having found several ways to turn pop-up elements into switches, we turned our attention to sensors. Our second page, shown in Figure 5, is also non-computational and explores paper-based potentiometers. It uses sliding and rotational motion to control the brightness of page-embedded LEDs. The left side of the page uses three coupled rotating wheels, with a rotational potentiometer in the center wheel, to cause three jellyfish to move and light up. As the handle on the wheel swings from left to right, two of the jellyfish become brighter and one of the jellyfish becomes dimmer. On the top right, sliding a tab also slides two fish down a sliding potentiometer. As the fish move, they become dimmer. Finally, on the lower right, as a handle swings back and forth, two sets of lights on a piece of coral alternate in brightness.

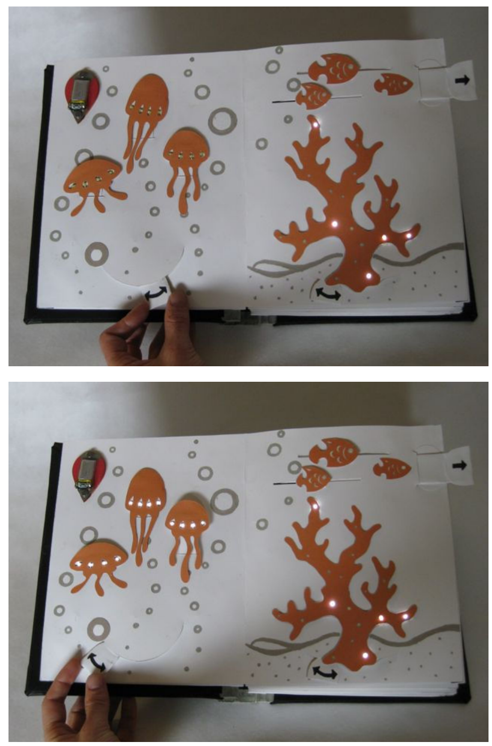

Figure 5. Top: with the wiper to the left the jelly fish lights are off. Bottom: with the wiper to the left the lights are on. When the wiper is in the center of its track the lights are dim.

The potentiometers were created by painting a resistor onto a page with resistive paint and then attaching a conductive mechanical wiper that moves across the resistor. In the rotating potentiometers, a diagram of which is shown in Figure 6, the resistors were painted onto steel impregnated paper and magnets were attached to the wipers to ensure robust connection between resistor and wiper at all times.

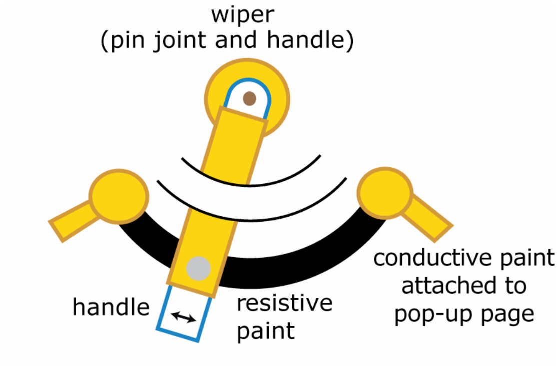

Figure 7. The rotator potentiometer mechanism

Page Three: Blue Skies and Skin Galvanic Response Sensors

The blue page was the first page we built that incorporated computation. It is controlled by the magnetic Arduino module and, in addition to page mounted LEDs, it also uses the magnetic speaker module. When the page is opened, a display of stars and clouds rises up out of the page as can be seen in Figure 8. When the Arduino is placed onto the page and turned on, "Twinkle Twinkle Little Star" begins to play and LEDs flash in a pattern in sync with the music. When the user touches both of the large grey stars on the page, the tempo of the music increases. The more pressure the user applies to the stars, the faster the tempo becomes.

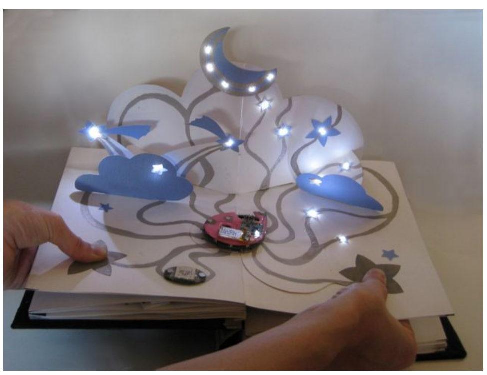

Figure 8. Top: When a user touches both of the silver stars, the tempo of a song played by the page increases.

This sensor, a skin galvanic response sensor, measures the conductivity of the user's body. It is created by connecting one conductive surface to an input on the Arduino and another conductive surface to ground. When the user touches both surfaces, the Arduino detects how resistive the person is. The harder the user pushes on the patches, the lower the resistance is between the two surfaces. (We do not include a diagram of this sensor because of its simplicity.)

Almost all of the circuitry for this page is painted directly on the top surface of the paper—very little is hidden from view, as can be seen on close inspection of Figure 8. All of the painted lines lead back to the central microcontroller. At the joints between the pop-up panels and the rest of the page we reinforced our circuits with conductive fabric, which—as we mentioned earlier—can fold repeatedly without breaking.

Page Four: Yellow Solar System and Pressure Sensors

The yellow page is another non-computational page that uses a piezo resistive elastomer—a material whose resistance changes in response to compression—as a pressure sensor. When the page is opened, a spherical slice-form that represents the sun pops out of the page. By pressing on different planets on the flat part of the page, the user activates assorted behaviors: when the user presses Pluto, the sun gradually lights up, growing brighter in response to increased pressure. Squeezing Uranus causes Saturn's rings to glow. Pushing on the earth causes the moon to dim, and, finally, pressing on Mars triggers an embedded motor that makes Venus vibrate. Images of a user interacting with the page can be seen in Figure 9.

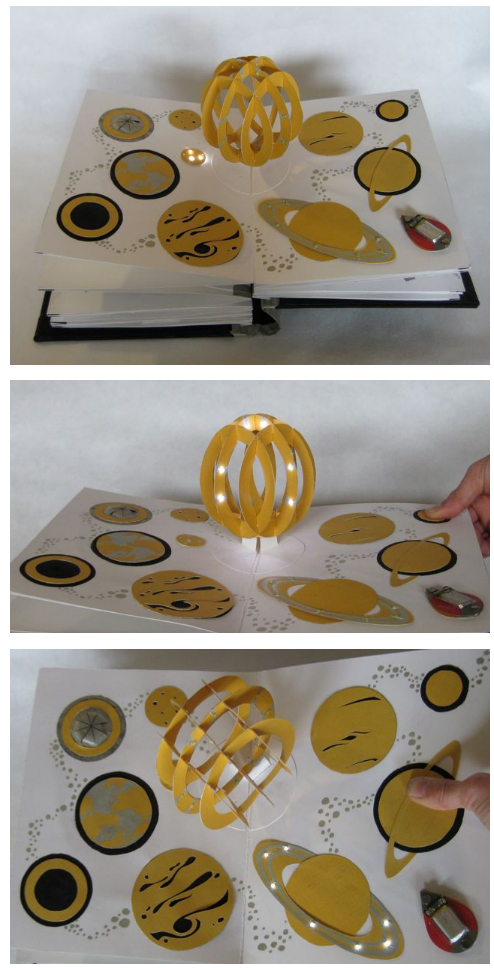

Figure 9. A page with embedded pressure sensors responds to pressure in different locations.

The pressure sensors were all constructed by sewing the piezo resistive material to the page with a silver-plated conductive thread [11]. The piezo resistive material has infinite resistance until it is compressed. When a user squeezes the material it begins to conduct, connecting the conductive threads. Increased pressure results in increased conductivity through the material. After the sensing elastomer is sewn to the page, an insulating fabric is glued over the material to secure the sensor. Finally a thick decorative paper, which distributes pressure more evenly across the sensor, is glued on top of the insulating fabric. A diagram of this sensor is shown in Figure 10.

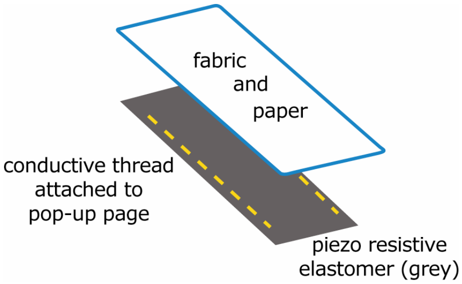

Figure 10. The pressure sensing mechanism.

The rest of the circuitry in this page includes conductive thread, paint, and copper tape.

Page Five: Purple NYC and Bend Sensors

The fifth page, shown in Figure 11, employs the magnetic speaker and Arduino, and a custom made bend sensor. When this page is opened, a cutout of the New York City skyline rises up. The bend sensor is hidden inside a flap that is shaped like a sailboat that lies on the page. When this flap is lifted, the buildings light up in four stages—the lower stories first, then higher stories, until finally all of the lights come on—and the speaker plays four rising notes.

The buildings were laser cut so that windows—holes in the paper—make up most of the facades, giving the buildings a lacy effect. Lights are soldered into the holes, so that windows appear to glow. To make the traces, the paper cutouts were carefully painted with conductive paint so that traces follow the exact geometry of the paper making up the building.

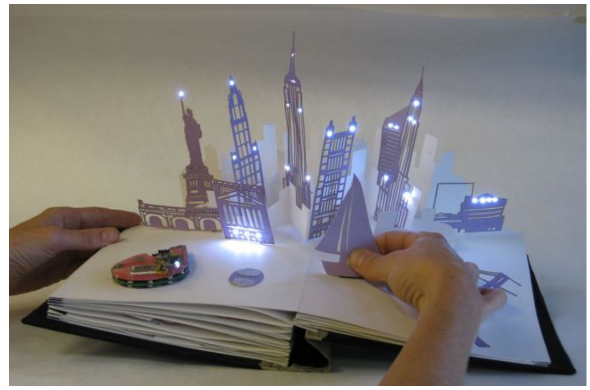

Figure 11. A bend sensor (labeled with an arrow in the top image) controls the lights in the skyscrapers. In the top image the sensor is flat and only the bottom-most lights are on. In the bottom image, the sailboat is fully erect , causing all of the lights to shine.

The bend sensor, a diagram of which is shown in Figure 12, was constructed by sandwiching two layers of conductive fabric between three layers of Velostat—a thin piezo resistive plastic. This sensor functions similarly to the pressure sensor described in the previous section. When a user bends the sensor, the velostat is compressed and its conductivity increases thus decreasing the resistance between the two conductive layers.

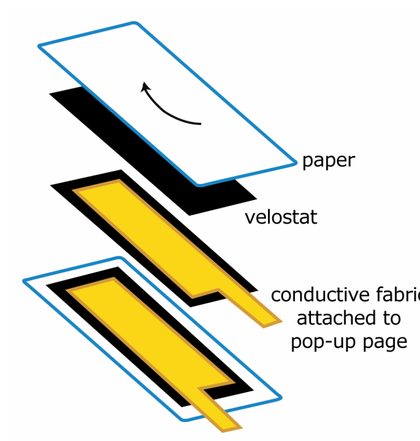

Figure 12. A bend sensor.

Page Six: Green Venus Flytraps, Capacitive Sensors, and Movement

Our final page, shown in Figure 13, employs the magnetic Arduino and an additional magnetic battery module. When a user turns to this page, six Venus flytraps spring up from the page. When a user touches the center of a leaf it closes around her finger like a Venus flytrap.

To achieve this affect, all of the leaves have springs made out of shape memory alloy—a nickel titanium, or “nitinol” wire—embedded in them which allows them to fold open and closed. A spring contracts and closes its leaf when it is heated by an electrical current. A leaf reopens when the wire cools and the force of the paper pulls the spring open again.

Figure 13. Capacitive sensors trigger nitinol-driven flytraps. Top: a user touches a sensor. Bottom: a trap in its open and contracted states.

Three leaves have capacitive touch sensors embedded in them to detect user interaction. Each touch sensor is composed of three layers: a ground layer, an insulating layer, and a sensing layer, as is shown in Figure 14. The sensing and ground layers can be constructed from conductive paint, fabric, or any conductive sheet. The sensing layer is attached directly to one input pin (pinA) on the microcontroller and to another pin (pinB) on the microcontroller via a high value (~10M Ohm) resistor. The microcontroller alternately drives pinB high and low, while monitoring the time it takes for pinA to "follow" this signal. The follow time will change when a user touches the sensing surface, thus enabling the microcontroller to detect interaction.

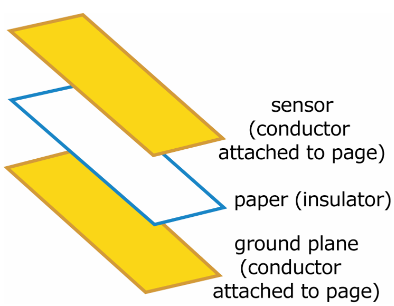

Figure 14. A diagram of the capacitive sensor.

Most of the circuitry for this page was made with copper tape and insulated wire-wrap wire due to the need for high current (and therefore low resistance) circuitry to heat the nitinol.

CONCLUSION: MATERIALITY, FUNCTIONALITY, AND BEAUTY

When he coined the term ubiquitous computing, Weiser envisioned a world where computational devices, embedded in physical artifacts everywhere, would disappear seamlessly into the background of our lives, enhancing our productivity, efficiency and comfort without claiming much of our attention [23]. Though powerful, this point of view is incomplete. Technology should not be exclusively devoted to increasing our productivity or comfort, neither should it always be unobtrusive. In addition to pursuing Weiser's eloquent vision of transparent supportive technology, we should strive to develop artifacts that enrich our lives by being entertaining, provocative, and engrossing [18].

The aim of this paper is to provide an example of this type of artifact: a device that is (we hope) unique, beautiful, and captivating as well as functional. By describing the materials and techniques we employed in our exploration, we also want this paper to serve as an example of an under-utilized and fruitful style of interaction design, one that integrates experimentation with physical materials with an exploration of the functional and aesthetic affordances of computational media.

Materiality, functionality, and beauty are deeply related. When one builds a chair, for example, there are functional and aesthetic implications to choosing a particular wood or upholstery fabric for its construction. Computation has allowed us to escape from many of these physical constraints, and their accompanying design traditions. Computational media, in its intrinsic abstractness, gives us extraordinary power to decouple behavior from material. Thus a cell phone can sound like a bird, a trumpet, or a police car; a computer can work like a sketchpad, a camera, or a library. This incredible power and flexibility has limitations however. The majority of today's computational devices are still hard, drab-colored boxes. Integrating interaction design with an exploration of physical materials expands designers' creative toolbox, enabling them to construct devices that look, feel, and function very differently from the boxes we have become accustomed to.

It is not enough however to incorporate a broader range of materials in interaction design. It is only through explicitly acknowledging the dual importance of aesthetic and functional design that designers will exploit the full potential of any medium. In striving for aesthetic affects, new functional and material properties are uncovered. Conversely, material and functional constraints give rise to new styles and ways of seeing.

In the admittedly modest—but we hope still-compelling—example of our pop-up book, working in an unusual medium and consciously addressing materiality, functionality, and beauty enabled us to: develop new engineering techniques, like our sensor construction methods; explore new artistic territory by endowing pop-ups with an expanded range of interactivity; and discover useful new materials like resistive paints and steel-impregnated paper.

ACKNOWLEDGMENTS

Removed for anonymity.

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