Fabricating Bendy:
Design and Development of Deformable Prototypes

The Bendy prototype was designed to study deformable user interfaces that mimic potential commercialized flexible devices. Its fabrication process uses inexpensive, readily available materials that can be easily customized to develop prototypes for other interaction research.

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Despite rapid advances in flexible display technology over the past decade, such technology is not yet readily accessible to researchers who study deformable interactions and user interfaces.[1,2] In lieu of active flexible displays, researchers have employed different techniques and methodologies to create low-fidelity prototypes.[3–5] Such prototypes provide preliminary iterative exploration and proofs of concepts while keeping development costs low and fabrication times short. However, the prototyping process often overlooks giving users an authentic product experience.

Deformable gestures are types of input that physically deform an object—for example, bending, twisting, folding, or stretching the object. These forms of input are appealing because they leverage the physical actions we use intuitively to interact with real objects, so a prototype's form factor is important to deformable interaction research. How does the prototype feel? How robust is it? Is it easy to deform? Proof-of-concept prototypes that rely solely on digital experience are insufficient for products that are inherently integrated with physical actions.

We present the fabrication of Bendy, a deformable prototype, using basic software knowledge, simple fabrication techniques, and readily available materials (see Figure 1). In this case study, we describe our design and fabrication process, demonstrating its adaptability for building robust flexible prototypes that support in-depth deformable interaction research in the absence of true flexible display technology.

Designing and Fabricating a Deformable Prototype

Although truly thin-film flexible displays are unlikely to be commercialized in the near future, the Kinetic prototype,[6] PaperPhone,[1] and PaperTab[7] demonstrate three types of functional flexible devices (see the "Related Work in Deformation Interactions" sidebar). We were particularly inspired by the Kinetic device, with its smartphone dimensions and flexibility. It was also closest to a commercialized product. We leveraged its physical affordances to inform the design decisions we made during Bendy's development.

Bendy's hardware design involved an iterative process to address a real product's physical affordances, enable the prototype's interactivity, and ensure robustness that could withstand the prolonged use of an interface for a study of arcade games. The result was a three-layer construction consisting of a plastic substrate, a flexible circuit layer, and a silicone layer (see Figure 2). It uses projection for visual feedback to emulate a flexible display.

The application requirements guided design decisions relating to size, material stiffness, and interaction language. In our case, Bendy is the size of a small tablet (120 mm × 170 mm × 3 mm).

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Its materials are flexible enough for comfortable use over a long period, yet resilient enough to return to a neutral state after repeated deformations. To provide input for our arcade games, we created a detailed bend-gesture interaction language consisting of 20 unique bend gestures: four corners, four sides, and *x* and *y* axes, in both directions.

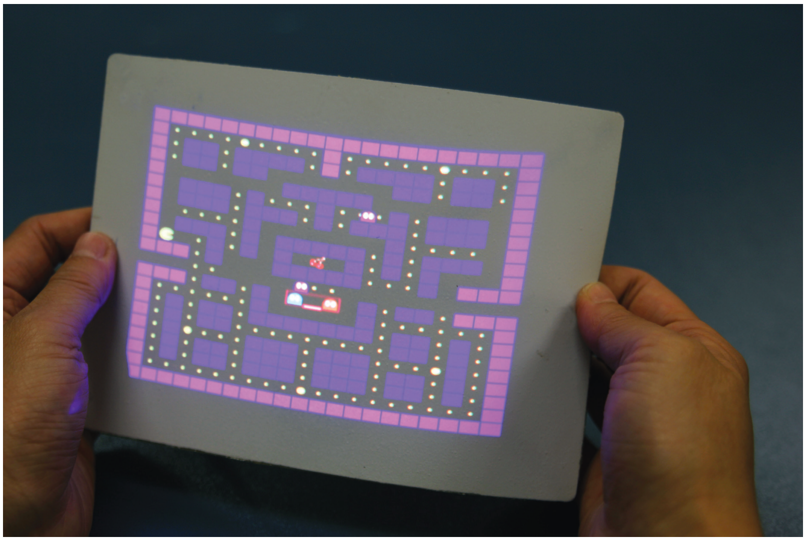

Figure 1. The Bendy prototype for playing arcade games. We designed and fabricated Bendy to enhance deformable interaction research using bend gestures.

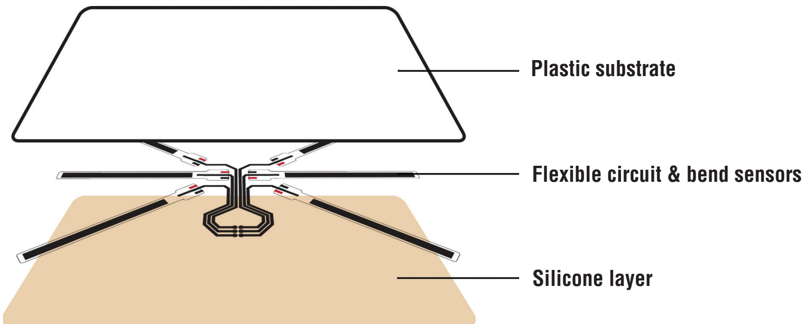

Figure 2. Bendy hardware design. The prototype consists of three layers: a plastic substrate, a flexible circuit layer with bend sensors, and a silicone layer.

Material Composition and Flexibility

Bendy is composed of two main materials: the plastic substrate and the silicone layer. We experimented with several different compositions of plastics and silicone Shore hardnesses to achieve our desired product requirements. (The Shore hardness level refers to the measure of the material's resistance to permanent indentation.) Researchers can easily customize the plastic and silicone hardness and vary thicknesses to fit their purposes. For example, if researchers want to create an elongated flexible device that retains its shape after deformation and has more rigidity than an eraser, they could use a shape-retaining plastic and a silicone resin with a Shore hardness of 70A. Ronit Slyper and her colleagues used a Shore hardness of 10A for very flexible prototypes in a variety of form factors.[8]

The plastic substrate can be any flexible plastic that can withstand prolonged use without permanent deformation (unless that's a desired property). We experimented with polystyrene and polycarbonate for the plastic substrate. Although polystyrene provided the desirable rigidity, prolonged use of the prototype caused undesirable permanent deformation. In addition, bending beyond 90 degree angles caused the material to break. Conversely, polycarbonate is a more rigid plastic that retains its shape after extended trials and resists breaking even at extreme deformations.

We subjected the prototype to many trials, bending the device repeatedly and retesting the circuitry for functionality. It is difficult to quantify exactly how many bends the plastic can withstand, but in Bendy's case, the plastic substrate withstood two months of repeated use before exceeding its strain (breaking or permanently holding a curved shape).

Silicone resin is available in different Shore hardnesses, which allowed us to create and experiment with prototypes of varying degrees of flexibility—specifically, we tested Alumilite Flex 70A, 60A, and 30A resins. We selected the Alumilite product because it did not require a vacuum or pressure chamber, which made it easy to use. We machine-milled a negative release mold to cast the prototypes.

We performed bend gestures on trial prototypes (see Figure 3) and found that performing our bend gestures was significantly more difficult with the gauges greater than 30A. We leveraged Johan Kildal and his colleagues' findings,[9] which indicated that stiffer materials were least preferred by users and, consequently, our design incorporated less-stiff materials. We anticipated that low-stiffness materials would minimize

Related Work in Deformation Interactions

Researchers have used a variety of prototyping methods to study deformable interactions. We surveyed the different techniques and methodologies, focusing on deformation sensing and visual displays.

Deformation Sensing

The key capability element enabling flexible prototype interactivity is the detection of physical deformations that users perform. Deformations can vary from simple one-axis bend gestures, such as bending a corner up,[1,2] to free-form deformations, such as twisting in many directions and locations at once.[3–6] Bend sensors and depth-sensing cameras are the primary tools for detecting deformations.

Bend Sensors

Strain gauges are the most common approach to detecting deformation.[1,3,4] A strain gauge—or in our context, a bend sensor—measures the change in electrical resistance during physical deformation. It is composed of carbon-resistive materials and works as a variable resistor.

For electronic prototyping, many manufacturers offer inexpensive bend sensors (US$5 to $15), depending on lengths and features. These sensors are easy to use and can connect to any microcontroller with an analog-to-digital converter, such as an Arduino microcontroller.[7] Multiple-bend sensor configurations allow for varying deformation complexity. Researchers have also successfully designed and built their own bend sensors.[8,9]

Camera Sensing

Cameras can also detect deformation. David Gallant and his colleagues devised a rapid-prototyping method using black cardstock, which they augmented with infrared reflective markers and tracked with a webcam modified to use infrared LEDs.[10] However, the prototype was used only as an external device because the markers interfered with the display surface.

More recently, the FlexPad system advanced this method by using a depth-sensing camera (specifically, Kinect) to make the process markerless and adding the capability to track detailed and complex surface deformations.[6] Although this method has advantages, it requires expert knowledge to develop a complex algorithm, therefore rendering the method inaccessible to many researchers.

Visual Displays

Deformable prototypes must also give users visual feedback. Figure A shows three options: flexible, rigid, and projection displays.

PaperPhone was built using a 3.7-in electrophoretic, or E Ink, display (www.eink.com/technology.html), augmented with bend sensors (Figure A1).[7] Although E Ink displays are the first to use a functional display, most of them are limited to gray-scale screens and a slow refresh rate, which is restrictive when displaying dynamic content. Another flexible prototype, the Nokia Kinetic device, overcame this challenge by using a flexible, color organic light-emitting diode (OLED) display and a strain gauge to detect bends and twists.[4] However, both prototypes contained rigid parts that limited the interactions to simple bends.

With availability and cost limiting access to flexible displays, researchers have substituted rigid displays or projected images on flexible substrates. Affixing a rigid display onto a piece of flexible plastic augmented with bend sensors (Figure A2) eliminates the gulf of execution, which makes it easier for users to perform the intended task.[11,12,13] However, it also prevents the form factor from being fully flexible; only a small portion of the prototype is deformable.

To address these drawbacks, researchers have projected images onto flexible materials to simulate a flexible display (Figure A3). Using markers or depth sensing, a camera detects the prototype's position and orientation and projects an optimized image on the deformed surface.[2,5,6,13,14] The projector offers a lightweight, versatile solution to creating deformable prototypes that display dynamic information. However, measuring the prototype's deformation to calculate and correct image distortion can be a challenge, owing both to screen occlusion and to programming limitations.

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fatigue when used repeatedly for long periods. Guided by the design of possible real flexible devices, we found that the combination of 30A silicone and polycarbonate provided an optimal amount of flexibility and durability.

We experimented with several ways to encase the circuitry in the silicone. In the first trial, we directly submerged the circuit into the silicone resin. This method proved difficult, tedious, and inaccurate owing to the resin's limited working time (5 minutes). So we introduced the plastic layer, which included the adhered circuits, and cast the silicone resin on top. The silicone resin has inherent adhesive properties, so it bonds to the plastic's surface.

This process also allowed for a smooth surface finish on both sides of the prototype.

Sensor Configuration and Flexible Printed Circuit

After determining a prototype's material composition, the next step is designing the sensor configuration to enable the required bend gestures. In Bendy, to measure 10 bend locations, we placed four sensors in the corners and two sensors centered on the left and right sides (Figure 4a). We used 3-inch unlaminated FlexPoint Sensor Systems bend sensors.

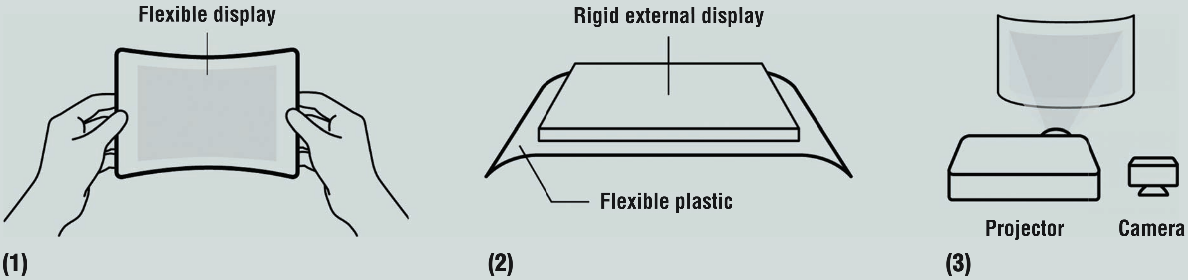

Figure A. Types of visual displays for deformable prototypes: (1) flexible, (2) rigid, and (3) projection.

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We selected the sensor size to correlate to the prototype's size and the bend's desired magnitude. We preferred unlaminated over laminated sensors, because the latter tended to ripple after extended use when affixed to the substrate, causing anomalies in the data output.

Before fabricating a prototype, we recommend creating a mockup to test gesture recognition by taping the sensors to a piece of flexible plastic.

After testing the sensor configuration for gesture recognition, we needed a circuit to connect the sensors to the Arduino Uno Microcontroller, which we chose for its easy-to-use software and hardware prototyping capabilities (see Figure 5). To maintain a thin flexible form factor, we selected to use a flexible printed circuit (FPC). We drew the circuit paths using vector-based drawing software, but design software for a printed-circuit board would work as well.

Our circuit design comprised three separate layers, one for every sensor connection: data, positive, and ground. We printed the three circuits separately and adhered them on top of one another. Their nonconductive backing prevented them from bridging one another. The circuit paths are approximately 1.4 mm wide, and the

Figure 3. Trial prototypes using different types of plastic, silicone, and fabrication methods. Performing the application's bend gestures was significantly more difficult with materials having Shore hardnesses greater than 30A.

end points are spaced 0.1-in apart to maintain compatibility with a standard cable connector. We placed the connectors at the device's center, where the least stress occurs. We drew the circuits void of any right angles to also minimize stress points.

We printed the circuit on a single-sided DuPont Pyralux (LF9120) flexible copper sheet using a wax-based ink printer (Xerox ColorQube 8570DN). The wax ink protects the conductive paths because it is resistive to copper etchant. It is important to clean the copper and remove any oxidization, which can prevent the wax ink from adhering properly. After printing the circuit, we inspected the ink surfaces for any exposed copper. We mended gaps using a permanent marker (Sharpie), lightly dabbing the ink on top of the breached areas.

We etched the copper using a two-to-one ratio of hydrogen peroxide and hydrochloric acid. Etchants such as ferric chloride proved too corrosive in early trials, producing a pitted surface on the copper. After the copper dissolved, we removed the ink using isopropanol.

To assemble the prototype, we adhered the sensors first and then the FPC to the plastic layer. Although silicone has adhesive properties, they are not sufficient to properly bond the circuit and sensors. We therefore experimented with different bonding methods. We found that a flexible bonding adhesive (PlioBond) performed best for the sensors and a spray adhesive (3M Super 77) for the flexible circuits. We soldered the circuit's leads on top of the bend sensor's contact points to minimize stress points. We used L-shaped connectors to link the circuit's ends to the cable attached to the Arduino microcontroller. Figure 6 illustrates the fabrication process (also see the video available at http://youtu.be/PJ5ee5gAbm8).

Connecting Hardware to Software

Bendy's sensors and a calibration button are connected to an Arduino Uno Microcontroller. The calibration button lets the program normalize to the sensors' resting-state output, which can vary over time and after use. An Arduino program receives and processes the raw bend-sensor data. We set activation threshold values for the up and down directions. An algorithm calculates the bend gesture performed by determining which combination of sensors is currently activated. For example, it senses the top-side bent-up gesture if the top-left corner and the top-right corner sensors are both activated upward. The applications used for gaming (written in the Processing programming language) receive the bend-gesture output.

Replicating the Bendy Process

We tested our fabrication techniques on two additional flexible prototypes.

First, we designed a smaller version of Bendy that reproduced a smartphone instead of a small tablet. We used 2-in sensors and scaled down our original sensor configuration (see Figure 4a). The new prototype proved as easy to create as the original one and generated reliable bend activations.

Second, we designed a prototype to explore the use of corner-focused bends that minimized the user's hand repositionings. We created a new gesture language to give the user more bend possibilities within a single corner. In Bendy, each corner had only two gestures (up or down). In the second prototype, each upper corner had six gestures, by adding edge classifications to the location and direction, as described by Kristen Warren and her colleagues.[2]

This second mobile-phone-sized prototype had two 1-in sensors on each top corner and one 1-in sensor on each bottom corner (Figure 4b). The prototype let us manipulate the text cursor with a single upper-corner grip: bending the corner horizontally toward the user moved the cursor down the page, while bending the corner vertically away from the user moved the cursor right. So this prototype was not only a different size from Bendy but also used a different sensor configuration. The small sensors provided comparable gesture-recognition precision.

Creating a smaller prototype with a more complex sensor configuration

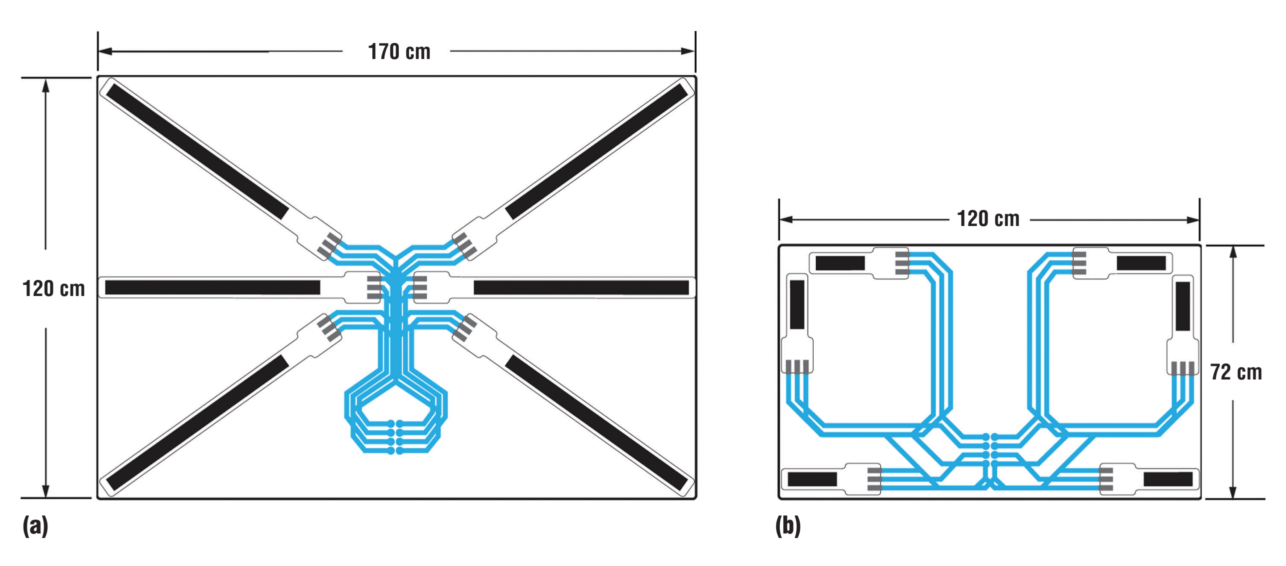

Figure 4. Sensor and circuit configuration for (a) Bendy and (b) a smaller form factor. Bendy uses four sensors in the corners and two centered on the left and right sides. The smaller form factor features a more complex sensor configuration, proving that the process used with Bendy is replicable and adaptable without effecting ease of fabrication and robustness.

proved that the Bendy process is replicable and adaptable without effecting ease of fabrication and robustness.

Discussion

The Bendy case study demonstrates how we can create a cost-effective, robust interactive prototype using a variety of accessible materials and simple do-it-yourself fabrication techniques. The process is efficient, taking approximately one day to fabricate a prototype from scratch. Each prototype costs less than US$70 ($10 per sensor, $1 per FPC, $1.50 per silicone, and approximately $5 in rudimentary materials such as glue, plastic, and copper etchant). However, capital acquisition expenses could increase the costs. For instance, the wax printer is currently priced around $600, although it doubles as a regular printer in our lab.

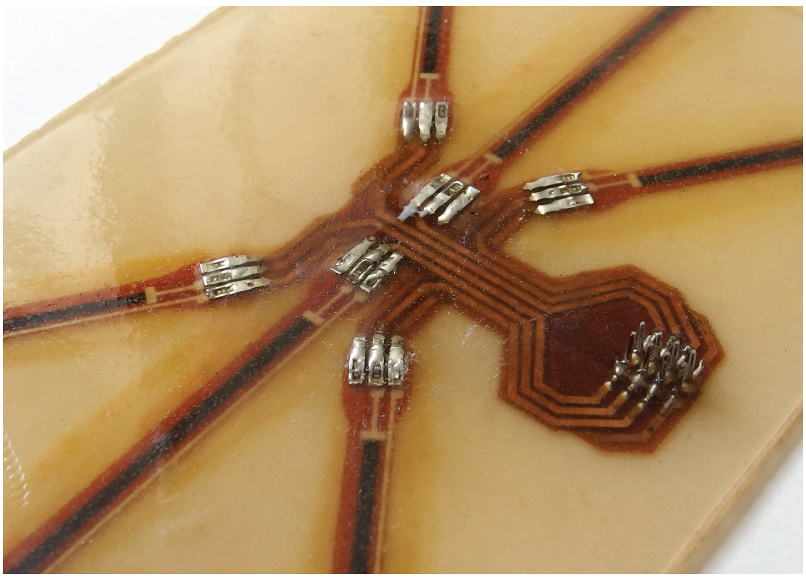

Figure 5. Bendy's flexible printed circuit, bend sensors, and L-shape connectors. The circuits sit on top of the flexible plastic substrate and under the silicone layer.

The process's replicability across different sizes, material compositions, and bend-gesture languages makes it highly customizable to suit different applications. In addition, the fabrication technique can adapt to sensors other than bend sensors. For instance, it would be easy to incorporate pressure sensors as buttons, LEDs for feedback, or accelerometers to obtain a device's movement in space. Each sensor type could connect easily to the FPC and be enclosed in the silicone layer. Researchers could augment the prototypes to extend beyond just bend interactions.

The Bendy prototype is limited by the lack of a functional display; it uses

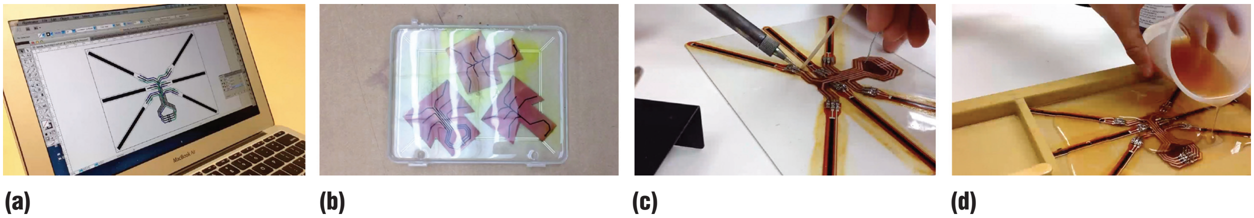

Figure 6. Bendy's fabrication process: (a) drawing the circuit, (b) etching the circuit, (c) soldering the components, and (d) encasing the prototype in silicone. The process is easily repeatable and works for a variety of materials.

projection to display dynamic output, which generates image distortion (see the sidebar for more information). Although we detected the prototype's position using a fiducial marker, we did not correct for image distortion. However, our application required only small bends, so we do not believe the distortion affected the research results. In future work, we hope to improve and integrate a better method to handle image distortion.

Our main goal with this project was to create an authentic product experience by building a prototype that would mimic potential upcoming, commercialized flexible devices. Deformable prototypes open many research areas—from flexible smartphones to deformable musical instruments to wearable computing. We believe that our prototyping method can extend to these domains and that it is accessible to researchers and designers without the need for expert prototyping skills. Assembling the prototype does require some basic technical skills such as soldering, and some of the procedures require safety protective gear.

Our future work will consider applying the Bendy process to other domains. We are also looking at ways to modify the procedure to include actual functional flexible displays—extending their display-only capabilities to create functional deformable devices. We have demonstrated our fabrication method's potential and look forward to testing it with users through a fabrication workshop.

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