# Living Paper: Authoring AR Narratives Across Digital and Tangible Media

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## Abstract
Storytelling is an important means for children to build literacy while sharing beliefs, values, and cultural norms. Our work investigates how augmented reality(AR) can fit into creative storytelling practices. We introduce Living Paper, a system for authoring AR narratives that span both digital and tangible media. Our augmented storybook prototype integrates animated AR characters from hand drawings with programmable LED lights that shine through the pages. Living Paper combines the flexibility of digital objects with the tangibility of physical cues to enable the creation of immersive and shareable stories.

## Author Keywords
Storytelling, Augmented Reality, Tangible Interfaces

## CCS Concepts
**•Human-centered computing → Mixed / augmented reality;**

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## Introduction
Digital storytelling is perceived as a powerful method for engaging children in teaching and learning [34]. Our research explores how emerging technologies such as augmented

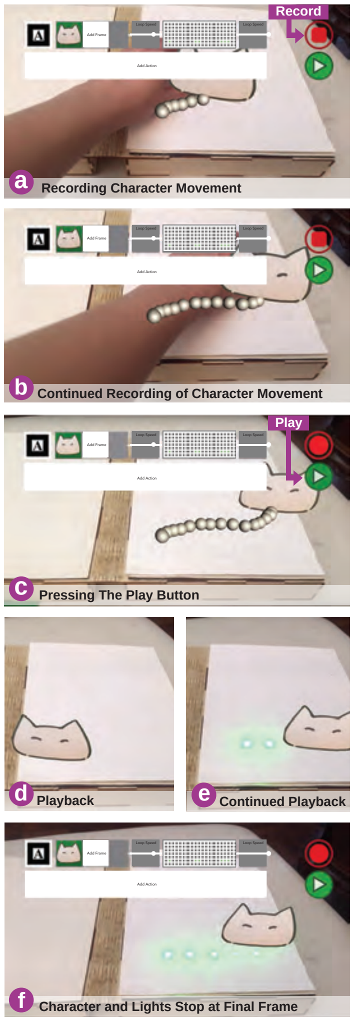



**Figure 1:** Character recording interface. **(a)** Press *record*, then user moves the marker. **(b)** White spheres get dropped along path. **(c)** User stops recording and clicks on *play*, to watch the **(d,e)** playback of the authored lights and the character's movement. **(f)** Once done playing, the full UI returns. (Note: UI text emphasized for clarity)

reality (AR) and tangible interfaces can offer new opportunities for children to create and share stories. Successful digital story creation tools usually follow known principles for creativity support tools [33, 36], such as supporting exploration, imposing a low threshold for learning while providing advanced features for advanced users, and supporting sharing and collaboration. We posit that these goals may be achieved by combining both digital and tangible aspects into storytelling.

Digital content in AR can be delivered through mobile-based augmented reality (AR), which is a flexible, dynamic and a widely accessible medium. However, these AR-based experiences have several shortcomings. Most of them are limited to the mobile screen and lack any form of tangible interactions with the environment other than movement. Many are designed with a focus on a single-user experience and the logistics of setting up multiplayer collaboration adds friction to their usage. Finally, AR often does not take advantage of familiar form factors (such as a book) or direct physical interactions (like drawing on paper and moving toys around) that children are used to. Prior work suggests [21] that such direct physical interaction facilitates learning and exploration and is a key factor for cognitive development during childhood. We wish to embrace this in our work.

Our system, Living Paper, uses tangibles to address some of the limitations in these mobile-based AR interactions. It provides users with a physical book embedded with programmable LEDs, which allows the user to feel like they are creating real artifacts as a part of their environment, and engages the curiosity of those around them. The value of such tangible and visible artifacts in an interaction has been indicated to aid in collaboration and cooperation amongst users [21]. With Living Paper, users without AR enabled devices can also actively contribute by drawing backgrounds on the physical book's pages and characters to later animate. Finally, using markers, we have created an alternative to timeline-based animation allowing children to replicate how they play with real toys, while allowing for creative freedom beyond that possible with purely physical or purely digital objects.

Living Paper is an instance of our investigation towards appropriate authoring interfaces and abstractions that enable children to author creative stories that blend digital and tangible elements. The contribution of our work is a mobile-AR based system that allows children to author stories through controlling both digital (AR character) actions and physical (LED light) actions using a single authoring metaphor and process that blends specifying action on screen and demonstrating behaviors in physical space.

In this work, our system employs a single-modality of tangible output — light — and tangible input — physical manipulation of AR markers. We aim to evaluate this, and use its results to inform the iterative design and development of an authoring system capable of multi-modal input and output through channels such as audio, vibration, force and physical actuation

## Related Work

*Tangibility and Augmented Reality*

While interactions in the physical world are predominantly tangible, digital interactions are mediated through input devices such as keyboard and mouse. Early work in Tangible UIs (TUIs) [8, 17] have been valueable in leveraging user's ability to perform rich multi-modal interactions. TUIs often involve interaction using natural hand gestures, and communication through such gestures has been shown to lighten cognitive load in adults and children [10]. Klem-

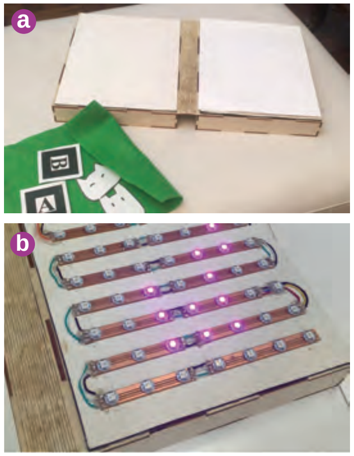



**Figure 2: (a)** Laser cut book with a living hinge spine, miniature green screen, cut out cat drawings, and image markers.**(b)** Grid of NeoPixel lights spaced out at a 1 x 1 inch resolution.

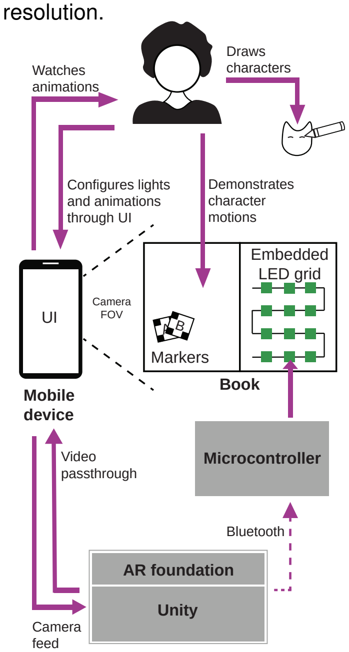



**Figure 3:** System Diagram

mer et. al[21] and Zuckerman et. al[39] further highlight the positive role of direct physical interactions in the cognitive development of children, on how these could enhance learning and exploration while performing a task.
In the meanwhile, the increased reliability and accessibility of mobile-AR devices such as tablets, delivers the promise of augmenting the tangible aspects of the physical world with digital content [15, 16]. This has allowed researchers to provide richer experiences to users. Magnenat et al's work [25] augments a coloring book with a digital 3D model anchored to it. The model gets colored digitally, as the user colors the cartoon on the page using a pencil. LEGO Hidden Side [24] presents users with an AR puzzle that is mapped over a set of physical LEGO blocks, and requires the user to manipulate the physical cubes to solve them.

*Storytelling*
Prior work has explored storytelling and how it can be supported with new media interventions. Boltman and Druin [4] examined the elaboration and recall of children's stories through a multivariate analysis, where one of the variables was media type. Their results indicate the positive role of *spatial presentation* in story telling. Prior works have also used physical props and tangibles such as toys[9], 3D cubes[18, 38], flat 2D cards [35, 37] and other custom objects[27, 26, 29] to control story lines, and have used AR or a physical display as a means to render the final output. Some works also leverage the traditional form factor of a book. An early attempt at this is MagicBook [2], which explores movement from physical space into virtual space and vice versa through an interface that has a physical book. Grasset et al. [11] studied the design space of augmented books and developed an implementation of it, defining semantics for mixed reality books, while other works use AR on top of an existing textbook for the purposes of learning and enhancing the user experience [20, 22, 12]. Alternatively, tangibles have also been used to deliver story in a richer way and these works build off of Ishii et. al's TangibleBits[17] work and extend them for the domain of storytelling by varying ambient lighting and sound [3, 13].

These works show the potential benefits that can be achieved by a combination of Tangible interactions and Augmented Reality. But, these interfaces require predefined content: They restrict users' actions to just a mere choice of story lines but enable them to make that choice in a tangible manner. Alternatively, they may also provide pre-authored AR stories that have some element of tangibility while experiencing them. However, these works do not allow for their complete authoring of the entire story end-to-end, by themselves. In contrast, our system, Living Paper allows for that. It leverages the imagination as well as existing practises of children, right from drawing their own character and animating them through hand sketching, the ability to author their movements in the scene through direct hand movements, controlling environmental effects through an directly mapped interface.

*Authoring AR experiences*
Authoring good AR experiences require significant effort. Feiner et al. [7] investigated automating the authoring of AR experiences for maintenance assistance. But these computational approaches often fail in Authoring AR content for creative domains such as storytelling [36]. WonderLAND [30] allows children to author and create simulated environments in AR that can be interacted with, in order to explore and learn science concepts. More sophisticated authoring approaches include block-programming using a scratch-style UI [31] and interactive computer-assisted authoring through story graphs [19]. We follow a performative approach [1] which may be more immediate and appropriate for children. Lee et al. [23]'s research lays out a design

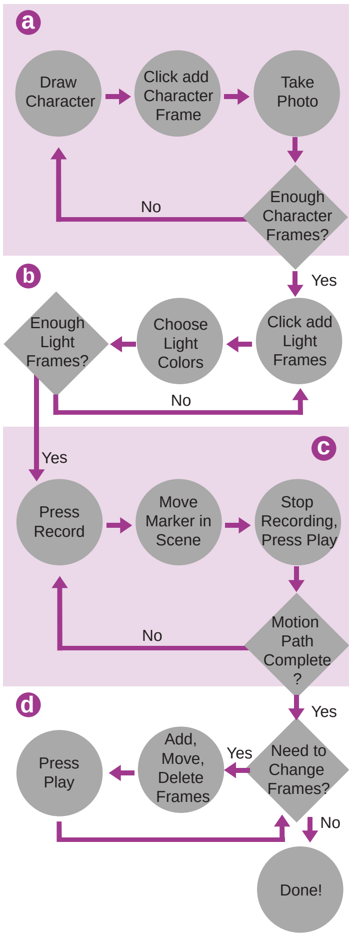



**Figure 4:** Workflow Diagram. This is one example of a workflow with Living Paper. A user can start with either **(a)** or **(b)**, and can do **(c)** then **(d)** at any point after having done **(a)**. **(a)** Stage 01: Animating a custom character, **(b)** Stage 02: Animating environmental light effects, **(c)** Stage 03:Defining character trajectories, and **(d)** Stage 04: Editing actions.

framework for immersive authoring using tangible markers as input for the outputted AR experiences. Like Lee et al. our work enables, authoring story elements such as characters, animations, trajectories and storylines. Living Paper differs from this in that, users can also author environmental actuation — lighting — as part of the storyline. For the latter, we base its design from prior research on paper-based electronics, such as PaperPulse [32] and Hello World [28].

## System Design and Implementation

The Living Paper system consists of three components: A physical book with programmable LEDs in the back cover that shine through the page (see Figure 2); A screen-space UI for creating animation loops (see Figure 6); and an embodied UI for adding character movement (See Figure 5). Reference Figure 3 for a system overview.

The basic workflow for creating a story, outlined in Figure 4, is as follows: **(1)** The user creates a stop-motion animation by photographing hand-drawn paper characters in different poses (see Figure 5); **(2)** The user adds an animated light effect corresponding to that animation (see Figure 7); **(3)** The character animation and light animation are mapped to a marker. The user hits the record button and moves that marker around to create a path (see Figure 1); **(4)** The animation is mapped onto that path, and plays at the same time as the lights.

As a simple illustrative example, the character animation could be a walk cycle, and the corresponding light animation could light up the LEDs along the path, one at a time from left to right. The user then hits record and moves the character marker from left to right across the back page, over the lights. The result of this (see Figure 1) would be some light effects that appear to trail the character as it walks across the page.

A more complex example of this system in use could involve various characters moving along in distinct paths and differently colored trails. The user would capture multiple animation sequences, each one assigned to its own marker, and record the markers' paths separately. The user can concatenate multiple paths for the same character, each with its own animation. Though, our current version focuses on LED Lights as a first step toward exploring tangible output, we envision that future work would expand to other forms of actuation.

### *Hardware Implementation*

The book is laser-cut out of wood, with a living hinge as the flexible spine. It contains blank pages, which the user can draw on to set the scene. The book's back cover contains an Adafruit Feather M0 chip, which is used to control the LED lights. The user interfaces with the chip via Bluetooth using a Bluefruit module.

The back cover of the book also contains a 7x7 array of NeoPixel LEDs in series (See Figure 2b). We created a custom PCB for each row of NeoPixels; this modular system easily allows more rows to be added later. The user can set each NeoPixel's 8-bit RGB value to create pixel art.

### *Software Implementation*

*1. Action Interface*

The *action interface* consists of a list of *actions*, each mapped to an AR marker. Each action consists of a series of *character frames* (Figure 6b), which are photos of user-created drawings, and a series of *light frames* (Figure 6e), which are sets of user-specified colors for the book's LEDs.

The user adds a character frame by taking a picture of an object against a miniature green screen. The app removes

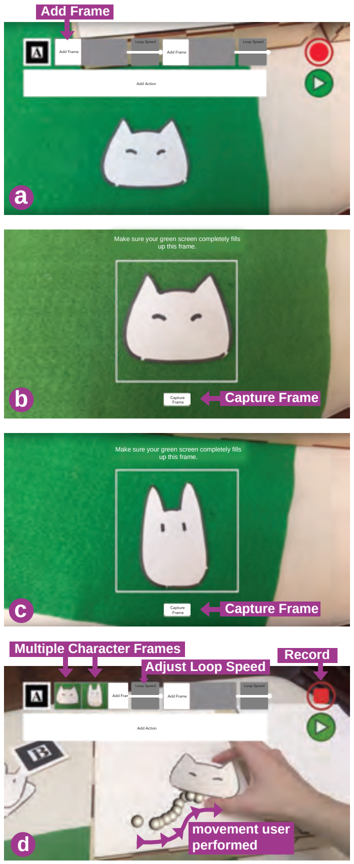



**Figure 5: (a)** User clicks on *Add Frame*, **(b)** and centers the cat character they drew and cut out in the frame and clicks *Capture Frame*. The background gets removed and a character frame is created. Image **(c)** shows the user capturing a second character frame. **(d)** Next the user clicks record on the top right, moves the marker and creates a path for that character's frames to follow. The *Loop Speed* determines how quickly to swap between the two frames captured. (Note: UI text emphasized for clarity)

the green background, creating a flat AR character, akin to a paper doll. Users can either draw, cut out, and photograph individual frames, or create paper characters with movable joints and pose them. They can also experiment with other media, like claymation or pose-able toys.

The user adds a light frame using a pixel art interface with a 7x7 grid of squares representing the lights in the book (Figure 7b).

*2. Recording Interface*
The recording interface is a tangible interface in which the user creates a motion path for a character, then maps a frame sequence onto that motion path.

Each action in the action interface is mapped to an image of an AR marker (Figure 6a), which in the real world is presented over a square wooden tile that acts as the physical AR marker. The user places the physical marker corresponding to their desired action in the scene, hits the record button, then moves the marker. Every 1/4 second, the system records and stores the marker's 3D location, represented in the scene with a sphere (Figure 5d). When the user hits play, the character cycles through the action's character frames while following the path. Simultaneously, the lights cycle through the action's light frames.

In the animation interface, the user can set the frame rate (Figure 6d) for the character frames and light frames individually, which changes how many positions on the path are mapped to one frame (ranging from 1 to 4, i.e., 1/4 second per frame to 1 second per frame). We refer to the frame rate as "Loop Speed" in the UI, which is a more understandable terminology for children. The frames will loop if the path contains more positions than the animation has frames. Although this is the typical use case, note that the system also allows advanced users to create longer frame sequences that won't loop.

To add to a character's path, the user hits record again with the marker still in the scene, and continues to move it. The system will concatenate the new path onto the existing path. Users can also modify the action for a marker by adding, deleting, or moving frames (Figure 6c) and any paths mapped to that marker will update.

We made the decision to forgo a traditional, timeline-based stop-motion animation process for a more tangible authoring mechanism in order to make this software more user-friendly. There is a subtle difference between video and animation timelines that has traditionally made animation timelines more difficult: video timelines consist of concatenated clips, while traditional animation timelines show individual frames and require the user to populate each frame with content. Our system emulates the "concatenating clips" idea, making a common, simple use case (looping character frames combined with movement) easy for beginners to work with, while retaining the power for advanced users to create more complex animations.

## Evaluation Plan

We intend to run a user study with children at the Lawrence Hall of Science, which has interactive exhibits designed for children. The children will be asked to create stories using Living Paper within a fixed time, and we will collect qualitative data regarding workload, usability and creativity support using the standard questionnaires - NASA-TLX[14], System Usability Scale (SUS)[5] and Creativity Support Index (CSI)[6]. We plan to analyze these scores as well as the individual dimensions of these questionnaires (e.g. *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Expressiveness*, *Enjoyment*, *Exploration*). For the quantitative

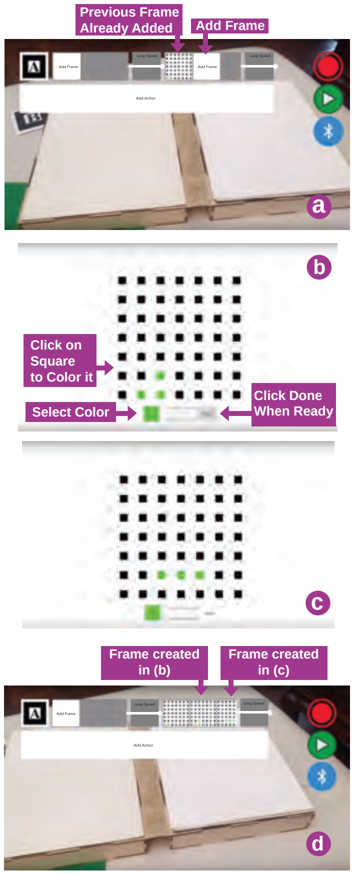
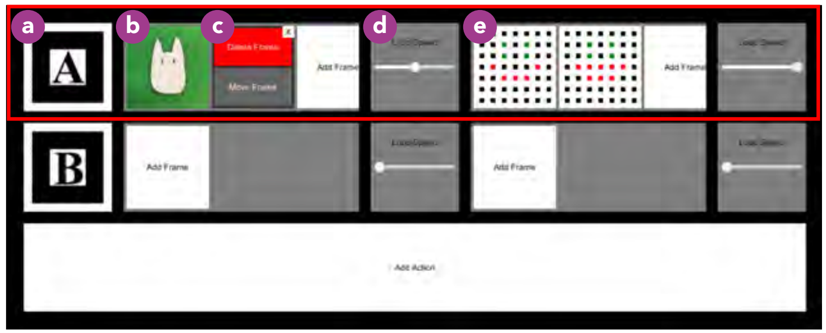



**Figure 7: (a)** User clicks on *Add Frame*, **(b)** and the *Lights UI* pops up. The user selects colors and squares they want to light up that color. **(c)** The same process is done for each light frame wanted. **(d)** Finally the user views all of their created light frames and plays them. The *Loop Speed* determines how quickly to move between the frames. (Note: UI text emphasized for clarity)




**a** The AR marker for the action outlined in red. Corresponds to a physical tile.

**b** The action's character frames (user-created drawings - green area gets removed).

**c** Menu that appears upon clicking an existing frame, enabling user to move or delete it.

**d** Char. frames' loop speed: how fast the char. cycles through them as it moves along its path.

**e** The action's light frames (user-specified colors for the book's 49 LEDs).

**Figure 6:** UI for the action interface. Each action (outlined in red), is mapped to a marker, and consists of both character and light frames, to encourage users to add lights to every action.

data, we plan to collect parameters indicative of interface usage and utility, such as depth of action steps created, average number of character and light frames used in each action, number of characters used in the story and total time taken. Besides these quantitative and qualitative parameters, we plan to follow it up with semi-structured interviews with the children along with their caretaker. By triangulating [36] these data, we intend to derive insights on whether Living Paper allows children to creatively author AR narratives that span digital and tangible media.

## Conclusion and Future Work

In this work, we have created an end-to-end pipeline for creating narratives that combine AR and tangible behaviors. The current prototype uses novel interfaces for creating and animating custom AR characters through hand sketching, and a recording metaphor that associates motion paths for AR characters with light animation patterns that take place in the same physical space (the page of the augmented storybook). Preliminary experiences with our prototype suggests it supports a high degree of creative freedom for creating the visual appearance and the behavior of characters in an tangible AR story.

These experiences also suggest several avenues for future technical work, in addition to the deployment and user study described above. First, the temporal authoring of AR behaviors and physical behaviors still follows two different paradigms: AR actions are demonstrated in real-time while light actions are authored frame-by-frame. We will investigate how to offer both types of authoring for both types of actions. Furthermore, we are interested in offering more embodied ways of editing already authored behaviors. Finally, we will investigate how to add other types of multimodal input and output, such as physical actuation, force, and audio, to Living Paper's authoring framework.

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