

MoveableMaker: Facilitating the Design, Generation, and Assembly of Moveable Papercraft

Michelle Annett^{1,2}

Tovi Grossman¹

Daniel Wigdor²

George Fitzmaurice¹

¹Autodesk Research ²University of Toronto

{mkannett,daniel}@dgp.toronto.edu {tovi.grossman, george.fitzmaurice}@autodesk.com



Figure 1. Moveables created with MoveableMaker, from left: a Pull to Translate storyboard, a Cobweb Halloween decoration, a Volvelle-based menu, a Pull to Translate instruction manual, a Slide-To-See quiz game, and a Rotate Lever math tool.

ABSTRACT

In this work, we explore moveables, i.e., interactive papercraft that harness user interaction to generate visual effects. First, we present a survey of children’s books that captured the state of the art of moveables. The results of this survey were synthesized into a moveable taxonomy and informed *MoveableMaker*, a new tool to assist users in designing, generating, and assembling moveable papercraft. *MoveableMaker* supports the creation and customization of a number of moveable effects and employs moveable-specific features including animated tooltips, automatic instruction generation, constraint-based rendering, techniques to reduce material waste, and so on. To understand how *MoveableMaker* encourages creativity and enhances the workflow when creating moveables, a series of exploratory workshops were conducted. The results of these explorations, including the content participants created and their impressions, are discussed, along with avenues for future research involving moveables.

Author Keywords

Animated paper; fabrication; interactive paper; moveables; papercrafting; prototyping.

ACM Classification Keywords

D.2.2 Design Tools and Techniques: User Interfaces; H.5.2. User Interfaces: Prototyping; H.5.m. Information Interfaces and Presentation (e.g., HCI): Miscellaneous.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from Permissions@acm.org.

UIST '15, November 08–11, 2015, Charlotte, NC, USA
© 2015 ACM. ISBN 978-1-4503-3779-3/15/11\$15.00
DOI: <http://dx.doi.org/10.1145/2807442.2807483>

INTRODUCTION

With the ever-expanding popularity of low-cost fabrication techniques, materials, and equipment, we live in a world where everyone is empowered to design, create, and make. From personalized jigsaw puzzles [17] to mechanical characters [3], what once required industrial equipment or expert artisanship is now within reach of everyone. As 3D printing and CNC machines stimulated a flurry of research into fabrication with plastics and woods, it is natural to assume that paper, arguably the most commonly available material for creative use, would follow.

While there has been renewed interest in paper in the domain of *paper computing*, recent efforts focus on the augmentation of paper with electronic components. By introducing power, switches, and light sources, a range of paper-based interfaces [2, 21, 25] or paper-based characters or robots [16, 31, 38] can be created. Although interactive paper has opened many avenues for exploration, it is the electronic components themselves, not the user, that initiate and generate interactivity. Given the physicality and organic nature of paper, it is also important to consider how to encourage and facilitate the user in interacting with paper itself.

Within the domain of paper engineering, *moveables* support this goal. A *moveable* is a papercraft in which the user touches or moves one or more elements to generate an *effect*. Effects can take on many forms, such as a hidden picture becoming visible when a flap is lifted, or an element moving when a tab is pulled. When used in books, moveables can transform an ordinary story into a unique, game-like experience that can spur an interest in reading, increase comprehension, and bridge oral and written language [20]. Although moveables have largely been relegated to children’s books, there are many broader domains where they could hold value, e.g., integrated within instruction manuals, used to prototype animation or software wireframes, create themed, interactive décor, provide new methods for skill building and knowledge, or create animated culinary menus (Figure 1).

Although the earliest moveables were conceived in the 15th century [11], the creation of moveables has seen little evolution in subsequent years, with design, generation, and assembly largely done by hand, with craft knives and glue. The process of creating a moveable is thus labor intensive and has largely remained inaccessible to those who are not paper engineers. We sought to develop methods and software that would enable users of any skill level to easily create, customize, and assemble moveables.

We present *MoveableMaker*, a new tool that enables users to design and personalize moveables, print and cut the necessary components using a paper cutter or laser cutter, and assemble their designs. To inform the design of *MoveableMaker*, a survey of over 500 children’s books was conducted to determine the prevalence of moveables and the variety mechanics used to generate effects. The survey results were further synthesized into a taxonomy and generalized goals for *MoveableMaker*. *MoveableMaker* currently supports the design and customization of 11 moveable effects, automatically generates moveable-specific instructions, allows for the usage of multiple materials, and intelligently decreases material waste, among other features. After describing our implementation, we report on the results of mini-workshops with novices and discuss the content that was created, user workflows, and the learnability of the software and participants feelings about making moveables.

RELATED WORK

Many previous projects have used technology to enhance paper engineering. We were inspired by work on paper computing, the animation of paper, and tactile books.

Paper Computing

The increased availability of conductive inks, paints, and copper tapes has inspired many to augment paper to enable interactivity. In *StoryClip*, Jacoby and Buechley explored how conductive ink and Arduinos could enrich children’s storytelling abilities [9]. Qi and Buechley extended this work into the domain of sketchbooks [25]. Qi and Buechley [26] also developed interactive books that use sensors and simple circuits to introduce dynamic story elements such as light, sound, or vibration. Buechley, Hendrix, and Eisenberg introduced a ‘construction kit’, with sensors, actuators, and microcontrollers, and conductive ink to add light, vibration, and sound to paper-based projects [2]. Mellis and colleagues introduced the “untookit” and associated software to assist with the integration of electronic components within papercraft [21], as did Ramakers, Todi, and Luyten [28]. Recently, Hodges and colleagues proposed replacing conductive ink with stickers [8].

Others have explored how paper can be enhanced in ways other than with simple electronics. For example, color-changing ink has been used to explore ‘electric origami’ [10] and interactive pictorial art [36]. Paper has also been extended past its commonplace usage for books and toys. Shorter, Rogers, and McGhee integrated electronics into 3D-paper headphones and a sound-based paper party invitation

[32], whereas Saul, Xu, and Gross developed paper-based speakers, lamps, and robots and presented a software tool to assist in the creation of geometries [30].

Within the present work, the focus is on supporting the creation of user-generated, paper-based movement and effects instead of on the integration of electronic components.

Animating Paper

In addition to enhancing interactivity, many methods have been explored to animate or move paper. Recent advances in shape memory alloys (SMAs) has been used to create a number of different effects, such as self-folding robots [5], self-folding origami cranes [27], paper-based moving toys [16], optical illusion art installations [4], and interactive post-it notes [24]. With *AutoGami*, Zhu and Zhao combined SMA with a software program to allow users to design and create simple animated characters [38].

Many other methods have been explored to create animations and motion. In *Flock of Birds*, Strohmeier and colleagues used stretch sensors, servo motors, and Arduinos to generate animation in a flock of origami cranes [35]. Niiyama et al.’s *Sticky Actuators* employ air-filled bladders to generate motion when attached to everyday objects such as cardboard boxes or origami [22].

Although the augmentation of paper increases its utility and the interactivity of characters and created content, the present work focuses on how motion can be achieved using commonly available materials and equipment and does not rely on electronics or prototyping techniques.

Tactile Books

Recent work has focused on the development of tactile books for children with visual disabilities. Initial work by Kim et al. explored how 3D prints could be integrated within board books [14, 15, 33]. Kim and colleagues later described a prototype development environment for the design of 3D-printed tactile books [34]. More recent work extended this to allow tactile pictures to be enhanced with simple movements [12, 13]. The present work differs in that we focus on the supporting the design of moveables and visual effects, and detail the development of software that interfaces with laser and paper cutters.

DECONSTRUCTING MOVEABLES

Although many are familiar with pop-ups or pull tabs, moveables can take many forms, such as greeting cards or as part of shadow boxes, with the most common instantiations occurring within children’s board books. With board books, one or more effects are added to provide the reader with interactive controls. We first explore the process of creating moveables, evaluate the current ecosystem of moveables, and then present a taxonomy of the moveables space.

Moveable Creation Today

Once an author has created a manuscript, they then work with a paper engineer to create a list of the effects they would like. Next, the engineer uses cardstock, glue, and craft knives to determine how to create the desired effect. In some cases, this

requires the engineer to create a mechanical system, in other cases they may only need to create cutouts or folds. Regardless of the mechanisms required, the engineer iterates over a variety of prototypes until the effect is achieved and can be manufactured for a reasonable price. Once a design is finalized, the moveable is deconstructed and each piece is traced onto tissue paper and scanned into a computer. The engineer then manually creates a set of instructions to be used by the assemblers of the book. The book publisher vectorizes the scanned components, adds any artwork, and prints the necessary components on cardstock. The components are then die cut, using custom-tooled dies and are then hand assembled. This process typically takes between six months to a year and a half per book.

Moveable Ecosystem

An analysis of existing children’s books was conducted to better understand the ecosystem of interactive, moveable books. Five hundred and four children’s books were selected from a large North American bookstore for evaluation. If a book contained interactive elements, we recorded: i) which unique interactive elements it contained, ii) the total number of interactive elements, and iii) the number of interactive elements per page.

Sixteen percent of the books selected contained at least one moveable element, with 797 moveable effects observed overall. This included a wide range of effects, such as: pop-ups, lift the flaps, volvelles (rotating wheels), slide to see tiles, lenticular lenses, mirror pages, tunnel books (i.e., a series of cut outs increasingly offset in size), and mix and match (Figure 2). Figure 3 illustrates the frequency with which each effect was found. This variability emphasizes the importance of supporting a variety of customizable and repeatable effects within our software.



Figure 2. Examples of effects found during the survey: (A) Mix and Match, (B) Slide to See, (C) Pull tab, (D) Tunnel, (E) Volvelle, and (F) a Pop-up.

On average, each book contained nine effects (Range of 1-50) with most having one effect per page ($M = 1.4$, Range = 1-8). This is mostly due to the physical limitations and dimensions of the required mechanical components. In books with multiple effects per page, only effects with small footprints such as lift the flaps or slide to see tiles were found.

If one can reduce the footprint of the components, it may be possible to include a variety of unique effects per page.

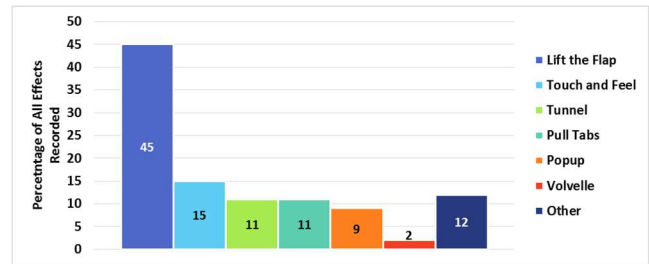


Figure 3. The prevalence of various effects in our survey.

The analysis also determined that most books utilized one of two of the same effects ($M = 1.5$, Range = 1-5). This may be due to the sheer effort and skill required to integrate a single moveable effect. When the instantiations of each effect within a given book were observed, many were slight variations of each other, e.g., lifting a flap up or to the left. It thus appears that automated software could be helpful in improving the variety and reusability of moveable effects.

Taxonomy of Moveable Technology

A number of moveable books were deconstructed and examined to understand the mechanics that generate various effects. The exploration determined that a single moveable is composed of three fundamental elements: the user’s interaction, the mechanical mechanisms, and the resultant effect (Figure 4). Although others have developed taxonomies to describe moving paper, our taxonomy does not focus on how paper can be manipulated, the number of sheets of required [37, 38], or exclusively on the mechanics used [7]. Rather, we take a holistic view of the complete process of interacting, constructing, and using a moveable.

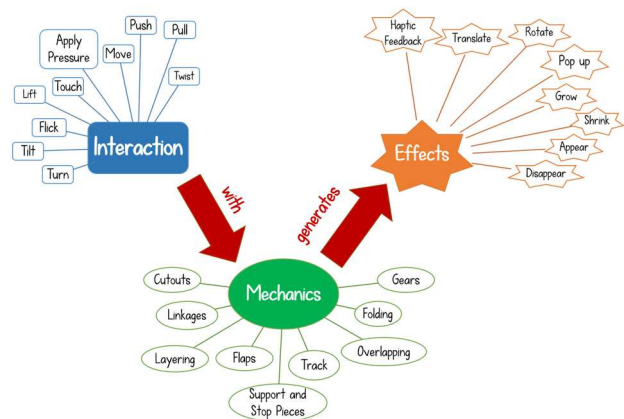


Figure 4. A partial taxonomy of moveables.

Interaction

Given that moveables are interactive, it is the user that initiates interaction. In most cases, this involves pulling or pushing an element such as a tab, rotating a wheel, or lifting a flap. Other examples include sliding a tile, or flipping or tilting a page. Although we only found examples of these

basic interactions, it is easy to imagine a variety of others including *twisting*, applying *pressure*, or *flicking*.

Mechanics

The mechanics of a moveable convert the user's interaction into an observable effect. This may involve converting the type, direction, or speed of the input motion (e.g., clockwise to counterclockwise, rotational to translational, and so on). Most moveables harness simple machines such as *linkages*, first class *levers*, *gears*, or *track* mechanisms, to generate output. Other moveables make use of *flaps* (e.g., one creased line that is manipulated by itself), *folding* (e.g., series of creased lines that create a pattern that can be manipulated at various points), *layering*, or intricate *cutting* techniques to generate visual output. As moveable mechanisms are the primary driver of manufacturing costs, there appears to be a tradeoff between using a chain of simple paper mechanics (i.e., linkages) versus gears. While gears are more durable, their production cost often impedes their usage.

Effects

The coupling of the interaction and mechanics can manifest in a variety of ways: content can *rotate*, *translate*, *appear* or *disappear*, *grow* or *shrink*, and so on. Most often effects are visual, but in some cases, the resultant effect can be *haptic* (e.g., Touch and Feel components allow the user to experience different haptic sensations), or *auditory* (e.g., the sound of a spinner rotating).

While we do not claim to be inclusive, the categorization of moveables along the dimensions of interaction, mechanics, and effects allows for a holistic understanding of moveable papercraft, whilst providing opportunities for future innovation. In addition to being found in the aforementioned moveables from the survey, these elements can also be combined in new and innovative ways to create a variety of novel animations and effects. For example, a folded flower could have weights attached to the petals, and when tilted in different directions, the petals could grow (i.e., open) or shrink (i.e., close). The taxonomy is also flexible enough to support moveables more complex than we found in our survey (e.g., moveables that employ a single point of interaction to generate multiple effects, or the use of multiple mechanisms to generate a single effect) and is not limited by the technologies or materials currently employed today.

MAKING MOVEABLES: MOVEABLEMAKER

We present *MoveableMaker*, a novel software tool that aids in the creation and assembly of customizable moveables. An explicit focus was placed on enabling the creation of those elements found in the moveable survey.

Goals

Based on our experiences with moveable books during the survey, five goals guided the development of *MoveableMaker*.

Permanency: One frequent issue with moveable books is that they often need repair due to repeated usage and the fragility of materials used. Any tools assisting in moveable creation

should support a range of materials, including support for quick prototyping and long-term use.

Reuse: Moveable effects are the result of hundreds of hours of hand work and are customized to specific pages or story elements. This decreases design and mechanic reuse. Our tool should allow users to easily create and reuse multiple instances of an effect and personalize them as desired.

Miniaturization and Scalability: Given the handmade nature of moveable mechanics, the precision and patience of the paper engineer often limit the size of components. The precise nature of computer controlled machinery and automation should be exploited to support the automatic rescaling of components to a variety of sizes.

Magic and Education: Renowned pop-up author Robert Sabuda believes that “[the Reader] shouldn’t be focusing on the “how” of the book; they should be enjoying the book for the sake of the experience”. Thus, it is important to balance maintaining the “magic” of a moveable for the user with the process required to create the moveable by the author. As such, the designs should be easy to assemble and create an experience that is enjoyable.

Personalization: One fault of moveables today is that they are void of personalization and are inherently generic. We should thus strive to support the integration of physical and digital content that is meaningful to the creator or user (e.g., family pictures, cartoon characters, and so on). This will increase the personal value to the user and the engagement of the creator during the production process.

System Components

The process of designing, generating, and assembling moveables requires the *MoveableMaker* software, a desktop printer, a *MoveableMaker* generated instruction file, and a craft paper or laser cutter (Figure 5).

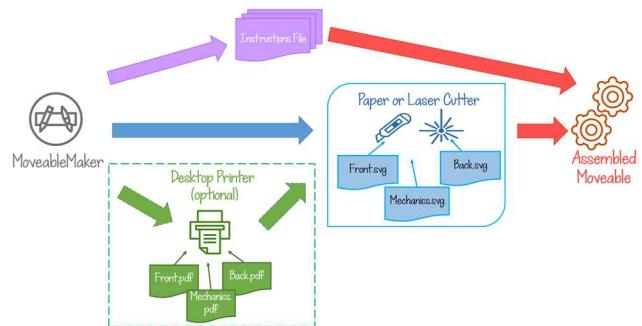


Figure 5. The process to create, generate, and assemble a moveable using *MoveableMaker*.

The *MoveableMaker* software was built using C# and WPF and is compatible with desktop computers and pen-enabled tablets. *MoveableMaker* allows for the composition of effects by dividing a given effect into the components needed for support (i.e., the Base Layer), the mechanics (i.e., the Mechanic Layers), and the visual effect (i.e., the Front Layers; Figure 6). Depending on the complexity or

dimensions of a design, multiple Mechanic or Front layers may be needed. For example, in Figure 6, the bird's body and sunrise would comprise one Front layer and the bird's eyes a second. Additionally, if only paper was available, one Mechanic layer would be generated, but cut multiple times and glued together to create thicker, durable gears. The use of a three logical layers not only educates the user about the effect, but also enables easier printing, cutting, and assembly.

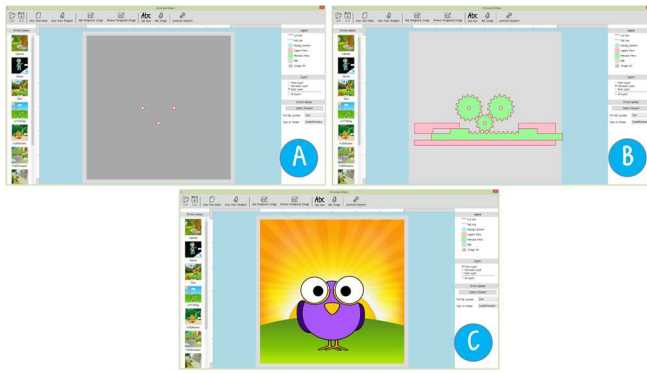


Figure 6. A Pull to Rotate effect, illustrating the (A) Back, (B) Mechanic, and (C) Front layers for this design.

Throughout, and at the end of the design process, MoveableMaker performs constraint checking to ensure that the design will print and cut properly (e.g., Do any components overlap? Can all components be cut using the materials available?). If the design passes the constraint checking and the user is finished creating their design, MoveableMaker generates .svg vector graphic blueprint files for cutting the Base, Mechanic and Front layers. If digital content was used, PDF files for the Base, Mechanics, and Front layers are also output for printing. Any PDF files that were generated need to be printed before they can be cut to the desired shape and size. After printing, the printed sheets are then cut. In our implementation, the Silhouette Cameo V1 hobbyist paper cutter and 5th Generation Full Spectrum Laser cutter were used for cutting. Once all components are print and cut, the design-specific instructions generated by MoveableMaker are used to assemble the moveable. MoveableMaker currently allows users to create moveables between 3" x 3" and 12" x 12". If plotters or larger paper or laser cutters are used, this can easily be extended further.

Supported Moveable Effects

Inspired by the analysis of the moveable effects that are commonly found in children's books today, nine of the most popular effects (with many customizable parameters) were implemented. Based on our experience with papercrafting and MoveableMaker, two new effects, the *Cobweb* and *Jaws*, were also implemented, for a total of eleven (Table 1; Figure 7). A layer-based deconstruction of each moveable effect, along with a temporal illustration, can be found Appendix A. As the graphics community has taken great interest in developing algorithms to generate pop-ups [6, 18, 19] and toolkits to support their creation, [7, 23], the present work focuses on the multitude of other moveable effects found

during the analysis. Note that, although the Touch and Feel effect does not create motion, it was included as it was the most prevalent in the survey.

User Workflow

The first step in creating a moveable is to use the MoveableMaker software. After the software is loaded, the user can use the moveable wizard to customize a pre-made design or start with a blank canvas. If the user chooses the blank canvas, the Effect Library on the left side contains the eleven effects that can be added to the canvas.

To ease understanding about the different effects, whenever the user hovers over an effect in the Effect Library, an animated tooltip demonstrates how the effect could be used, similar to Animated Icons [1]. These tooltips educate users in a way that is accessible by a variety of age levels. Once the user finds an effect they like, the effect is dragged onto the canvas. There are no limits to the number of effects that can be added, provided that they do not overlap each other. Because each moveable effect is visually rendered in the software using three layers, the Base and Mechanics layers are initially hidden from view to prevent confusion. The visibility of all three layers can be modified, however, using the radio options provided.

Users can customize their moveables in a number of ways. Effects can be rotated, translated, or scaled, with the underlying mechanics dynamically updated to accommodate new dimensions, customizations, or locations. If a user clicks on an added effect, customizable, effect-specific properties are shown in an 'Effect Options' pane (see Appendix A for the options that are available). In addition to having access to a digital library of foreground and background images, users can add their own photos, drawings, text, or freeform images. For the *Volvelle*, for example, one can customize the cutout shape geometry, the angle and location of the cutout shape, the location of the cutout for the user's fingers, the content to be printed on the wheel, and the type of wheel to be used (e.g., a smooth disc or a gear with teeth).

MoveableMaker also supports the freehand drawing of cutout shapes for the *Lift the Flap*, *Volvelle*, and *Touch and Feel* effects, along with freehand *Spinner* motion paths. To create a custom *Lift the Flap* shape, for example, the user can lasso around a subsection of a foreground image. The lasso then adapts to the contours contained within the lasso and the necessary cut and fold lines for the flap are generated.

As a number of different effects can be added to the canvas, and there are many effect-specific constraints, MoveableMaker uses a two-stage, heuristic-based approach to ensure that the designs created will print, cut, and assemble with little error. As MoveableMaker knows the footprints of all Base, Mechanics, and Front components (e.g. minimum gear sizes, inter-component spacing, and so on), the user interaction required to 'animate' each effect, the materials each effect can be created from, and the processes required for different materials, MoveableMaker continually evaluates

Table 1. Details on the various effects supported within MoveableMaker.

Effect Name	Mechanics / Description	User Interaction	Effect	Customizations
<i>Cobweb</i>	<ul style="list-style-type: none"> Series of intricate cuts creates a geometric pattern Hidden beneath the pattern is an image 	Pull a string attached to pattern's center	Hidden content appears	<ul style="list-style-type: none"> Geometric pattern Hidden content
<i>Jalousie (Blind)</i>	<ul style="list-style-type: none"> Two mirrored patterns are cut, one in the Front layer and a Pull tab The two sets of cut lines are interweaved 	Pull or push the tab	'Crossfade' effect	<ul style="list-style-type: none"> Pull tab location Hidden content
<i>Jaws</i>	<ul style="list-style-type: none"> Two first class levers have content attached as a load Brass fastener anchors the levers at their fulcrums 	Push together or pull apart the levers	Move attached loads in opposite direction of levers	<ul style="list-style-type: none"> Finger hole location Load's distance from center
<i>Lift the Flap</i>	<ul style="list-style-type: none"> An image is hidden beneath a shape cut out approximately 75%-90% of its path length and folded along the remainder of the path length (i.e., a flap) 	Lift the flap	Hidden content is revealed	<ul style="list-style-type: none"> Flap shape and direction Hidden content
<i>Pull to Rotate</i>	<ul style="list-style-type: none"> Rack and pinion system with the rack integrated within a pull tab Support and stop pieces restrict rack motion to prevent the rack from being pulled out of the gear system <ul style="list-style-type: none"> V1: Rack meshed with the pinion gear, which had the rotating content attached to it V2: Multiple pinion gears meshed with a rack V3: Two supporting pinion gears mesh with main pinion gear 	Pull or push the tab	<ul style="list-style-type: none"> V1: Rotate content V2: Rotate 2+ pieces of content V3: Rotate content in opposite direction 	<ul style="list-style-type: none"> Pull tab location Type of motion (i.e., V1, 2, or 3) Number of elements to rotate
<i>Pull to Translate</i>	<ul style="list-style-type: none"> Same as to Pull to Rotate <ul style="list-style-type: none"> V1: Uses a toothless pull tab and support and stop pieces V2: Double rack and single pinion gear system with two racks parallel to each other with mirrored gear teeth V3: Double rack and single pinion gear system with second rack rotated 90 degrees 	Pull or push the tab	<ul style="list-style-type: none"> V1: Content moves in the same direction as tab V2: Content moves opposite to tab movement V3: Content moves perpendicular to tab movement 	<ul style="list-style-type: none"> Pull tab location Type of motion (i.e., V1, 2, or 3) Number of elements to translate
<i>Rotate Lever</i>	<ul style="list-style-type: none"> First class lever Brass fastener to anchor the lever at the fulcrum 	Push or pull the levers	Attached load moves in opposite direction of lever	<ul style="list-style-type: none"> Load angle and distance from center Finger hole location
<i>Slide to See</i>	<ul style="list-style-type: none"> Sliding tile track, two hidden images, and a tile 	Slide the tile back and forth	Reveal the hidden image(s)	<ul style="list-style-type: none"> Slider direction Hidden image (i.e., right, left, slider tile)
<i>Spinner</i>	<ul style="list-style-type: none"> A cutout path in the Front layer A content spinner, (i.e., a foam spacer sandwiched between a disc-like weight and a balancing disc) that is wedged into the path 	Rotate and tilt the moveable	Weight causes the element to spin and move the attached content	<ul style="list-style-type: none"> Cutout path type
<i>Touch and Feel</i>	<ul style="list-style-type: none"> A cutout in the Front of the card or page and textured piece of paper or material cut slightly larger than the cutout 	Touch the textured material	Haptic sensations	<ul style="list-style-type: none"> Cutout shape Material
<i>Volvelle (Rotating Wheel)</i>	<ul style="list-style-type: none"> A disk, a cutout hole to view content, a cutout hole for the user's finger A brass fastener allows the disc to rotate about its center 	Rotate the wheel	Reveal content within the cutout	<ul style="list-style-type: none"> Wheel shape and content Cutout shape, angle, and distance from center Finger hole location Snake attachment



Figure 7. Examples of the user interaction possible with the (A) Cobweb, (B) Jalousie, (C) Jaws, (D) Lift the Flap, (E) Pull to Rotate, (F) Pull to Translate, (G) Rotate Lever, (H) Slide to See, (I) Spinner, (J) Touch and Feel, and (K) Volvelle effects.

5 - 12 constraints for each element on the canvas during the design phase (see the Appendix A for more details). A variety of *constraint-based rendering* mechanisms alert the user if their design violates any of the constraints or will be unsuccessful (e.g., dialog boxes, highlighted borders around problematic elements, elements that snap to edges,

dynamically resizing components, and so on). For example, for effects that require a cutout for the user's fingers along an edge, such as the Volvelle, whenever the user moves the effect around the canvas, the size of cutout dynamically resizes based on the distance from the edge (Figure 8).

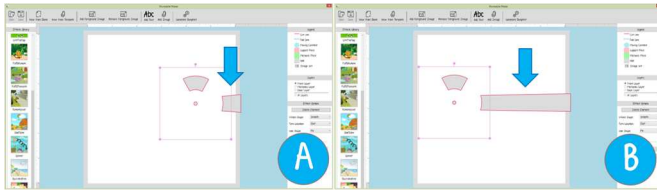


Figure 8. A demonstration of one of the constraint based rendering features with the Volvelle effect, where the size of the finger hole increases (A) as the effect moves farther (B) from the edge of the canvas.

Once satisfied with their design, the user clicks the ‘Generate Blueprints’ button, and is prompted to specify the materials they have available. As certain moveables have material limitations and requirements, another set of heuristics ensures that the design can be cut and assembled successfully (see Appendix B). The selected materials are cross-referenced with a database of material properties and effect-specific requirements. For example, if the user only has paper, cardstock, or chipboard, and an effect employing gears has been added, four blueprints need to be cut and glued together (i.e., two layers of 80lb cardstock to two layers of 100lb chipboard) to achieve the durability and stiffness required. As other effects require precise cut patterns in thin paper, such as the Jalousie and Cobweb, if paper and cardstock were not selected, the user is alerted via a dialog box and provided with suggestions to make their design successful.

MoveableMaker then generates the instruction file, vector graphic files, and, if necessary, PDF files for printing. The user then cuts the necessary pieces using their paper cutter, laser cutter, or so on, or can print the vector files and cut them manually using a craft or X-Acto knife. The user can then work through the instructions to assemble their moveable.

Automatic Instruction Generation and Assembly Assistance

Although the aesthetics and design of moveable effects are a crucial aspect of MoveableMaker, supporting the workflow that continues after the generation of the mechanic components is equally important. As such, MoveableMaker generates a complete set of assembly instructions for every moveable. MoveableMaker references a database of pre-specified assembly instructions, along with a hierarchical flow-chart that specifies the order components should be assembled (e.g., a Touch and Feel texture needs to be placed on the Base page before the translating content of a Pull to Translate effect is added). To ease assembly, MoveableMaker automatically populates the instructions with images that reflect the design one created. The instructions also specify any special materials that are needed, such as foam spacers, string, or brass fasteners. If the user does not have these elements available, the instructions provide details on where they can be purchased or how they can be made by hand (e.g., to replace a foam spacer, a stack of eight or ten paper circles can be used).

As the placement of content on the Base page is crucial to a number of effects, some Base pages will have a grey, guiding outline to indicate where sub-components should be placed

(Figure 9). This simple guide allows users to place component in the correct, precise location quickly and easily and eliminates issues that could be caused by poor alignment.

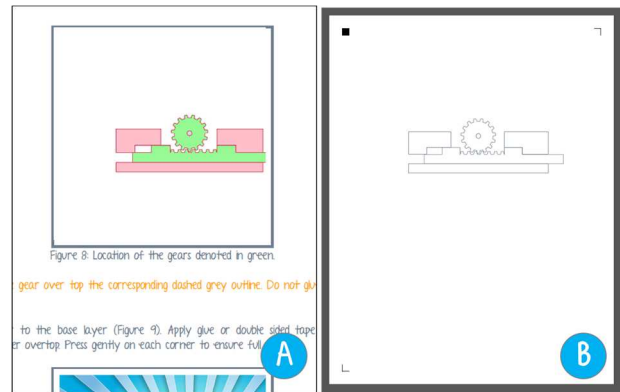


Figure 9. (A) The auto-generated instructions from MoveableMaker and (B) the corresponding Back layer .pdf file with the mechanic component locations outlined in grey.

Multi-Material Usage

Although MoveableMaker does not explicitly interface with laser or paper cutters, the use of the extensible .svg vector graphics file format allows the generated blueprints to be retargeted towards a variety of devices, including laser cutters, vinyl and paper plotters, and CNC machines. This allows for the use of a multitude of materials, including cardboard, wood, acrylic, chipboard, or cardstock to support both quick prototyping and the creation of moveables with increased durability for long-term usage.

Material Waste Reduction

With any system that uses materials, it is important to reduce the material waste that is the byproduct of tens or even hundreds of prototype iterations. As such, a Masonry Layout algorithm reduced the material waste from the Mechanics and Front layers. The algorithm finds the optimal location for each mechanical or front piece based on the vertical and horizontal space available on the output medium. To reduce the demands on the user to cut components, a user-based approach to material layout [29] was not used. The masonry layout also allowed control over the material tolerances needed by the Silhouette Cameo to cut thinner materials.

EXPLORATORY WORKSHOPS

As designing and creating moveables requires immense precision and extensive trial and error, any process that automates this inherently increases efficiency. As such, exploring the efficiency or timesavings of MoveableMaker would be impractical. Thus, small workshops evaluated MoveableMaker with respect to creativity, ease of use, learnability, and natural crafting workflows.

Participants

Nine participants were recruited within our local institution ($M = 29$, $Range = 19-44$, 4 female). Most participants were unfamiliar with moveables but had used an interactive book or greeting card with their child or received one as a gift. Only

one participant had tried to make a moveable before (i.e., a greeting card using a craft knife).

Method

Inspired by the workshop-style evaluation used in AutoGami [38], we held three workshops. Each workshop lasted 75 minutes and consisted of an introduction, guided task, free time, and feedback. During the introduction, the experimenters introduced and provided examples of moveables and briefly detailed the schedule for the session. To familiarize participants with MoveableMaker and the craft plotter, participants were guided through the design, cutting, and assembly of either a Cobweb, Volvelle, or Rotate Lever moveable. This required participants to use the MoveableMaker software, print and cut the generated blueprints using a printer and Silhouette Cameo machine, and assemble the moveable. The guided task took approximately 20 minutes. Once complete, participants were given 40 minutes to explore MoveableMaker and assemble other moveables. At the conclusion of the session, participants completed a short Likert-based survey (1 - Strongly Disagree to 7 - Strongly Agree) about their experiences with MoveableMaker, the generation and assembly process, and their overall impressions of creating moveables.

Supplies

To further spur creativity, a variety of scrapbooking materials was provided (e.g., patterned paper, foam sticker characters, adhesive letters, and so on). Participants were also free to bring their own digital content and had access to the MoveableMaker digital library and Google Images. An inkjet printer and Silhouette Cameo were also available. As the printer used standard 8.5" x 11" paper, the moveables that could be made during the workshops were 6" x 6". For safety reasons, a laser cutter was not made available to participants.

Discussion and Results

Feedback from the workshops was overwhelmingly positive. Many participants mentioned how fun it was to make moveables, and spoke of the "joy of seeing one of these [moveables] working - it's quite palpable ☺". All participants felt that MoveableMaker enhanced their creativity ($Mdn = 7$, $Range = 6 - 7$). One participant, who was not crafty, "enjoyed the use of technology to be creative" and said "MoveableMaker made the often difficult process of creating stuff on the fly less scary". Participants requested more time to continue designing moveables with MoveableMaker at the end of the workshops, e.g., "but I want to play more!", "can I have some more time? I just want to try this other idea I have out". All participants indicated that they would want to use MoveableMaker in the future ($Mdn = 7$, $Range = 6 - 7$).

Three participants expressed interest in the public availability and release date of MoveableMaker. Two wanted to use MoveableMaker with their children or as part of a team-building exercise with their co-workers. Another participant remarked, "I loved this! I would definitely hire this as a service for my kid's birthday party!" Many also felt that it would be great to use with children ($Mdn = 7$, $Range = 6 - 7$),

as in addition to supporting creativity, "it could also be used as a teaching tool about simple machines and mechanics".

Resulting Content

At the end of each workshop, participants created designs that were unique and personally meaningful (Figure 10). For example, one participant saw the Spinner effect and combined the effect with images of gears to create a spinner for his young son who interested in machines. Another, who was a video gamer, stated, "I am totally going to make a Last of Us themed moveable". While participants appreciated the breadth of moveables available, most harnessed effects that created motion, as opposed to simpler effects, such as lift the flap or touch and feel. Given that these motion effects were the least common in our survey, when using MoveableMaker, participants were inspired to learn about, and create, more complex moveables than those commonly found today.



Figure 10. Examples of moveables created by participants during the workshops.

In addition to motion, participants were eager to design their own effects, (e.g., "a hinged arm would be cool", "customizable gear trains") or use other materials ("it would be great to use magnetic sticker paper", "I would love to extend this to integrate simple electronics such as lights or sound"). MoveableMaker thus appears to stimulate the imagination and could be fruitful for empowering future creation and innovation.

At the conclusion of each workshop, participants were curious to see what others had made and expressed interest in mechanisms to share their designs (e.g., "I can't wait to share my [Last of Us] design with my online friends – they will be so jealous and want one"). Such comments are encouraging as they suggest the need to support online and offline social experiences around moveable creation.

Participant Workflows

During free time, two patterns of usage emerged. In some instances, participants chose to explore the software and then create their moveable. After exploring a variety of effects, these participants chose to use digital content exclusively and made frequent use of the printer. Other participants spent a great deal of time perusing the provided scrapbooking

material and prototyped paper combinations before they chose an effect (Figure 11). One participant liked an elephant foam shape and built their moveable around this element, whereas another was drawn to patterned paper and the idea of a “valentine” for his wife. Regardless of the workflow employed, many participants added pre-made content to their moveable after it was assembled “to punch it up”. The desire to use pre-made and digital content emphasizes the importance of supporting alternative workflows motivated by premade or personalized content or gifting goals.

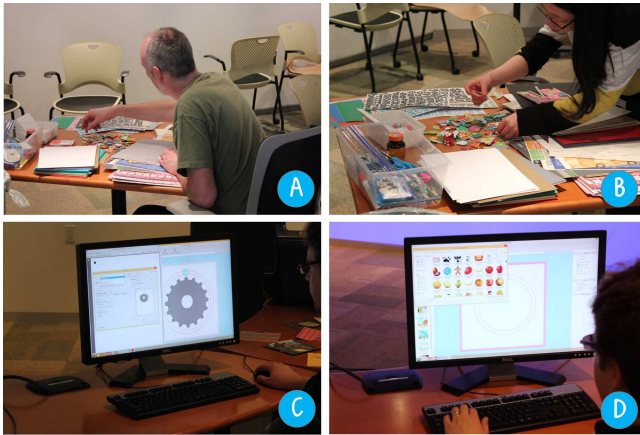


Figure 11. Different methods of interacting and constructing moveables observed during the workshops, where (A, B) pre-made or (C, D) digital content was used.

Although instructions were automatically generated for each moveable and participants found them helpful ($Mdn = 6$, $Range = 5 - 7$), some repurposed the ‘layers’ view to assist in the assembly process. Most participants used the instructions to create their first moveable and then used the ‘layers’ view to deconstruct the inner-workings of their other moveables. One participant said that this allowed him to use his new found knowledge during assembly. With another participant, instead of using the layers and feeling “confined in what I could make based on how I knew it would work”, she created and personalized her moveable using only the Front layer view and used the instructions later for assembly.

Ease of Use and Learnability

All participants were able to complete the guided task with little assistance and had little difficulty designing or assembling the rest of their moveables. The animated tooltips were a universally enjoyed feature ($Mdn = 7$, $Range = 7$) and helped many users develop a quick understanding of the effects that were available, “The animations made it really easy to pick which one I wanted”, “details like the animations for each effect were col”, “the gif effects were awesome”. Given the interactive nature of moveables, this was a welcome finding and suggests that additional animation-style elements such as simulations or support for automatic effect generation based on animated .gif input may be worthwhile to explore.

Many participants appreciated the unintentional educational aspects of the workshops. Although familiar with pull tabs and rotating wheels, many participants were unfamiliar with the terminology used to specify moveables, the underlying mechanics needed to generate an effect, or the materials used, (e.g., “I had no idea how these worked or were made before but now I understand why my children’s books break – the mechanics and materials used in books are just not that good”). As many of moveable effects are based on simple machines and mechanical devices, MoveableMaker may thus be viable within STEM or education settings as well.

FUTURE DIRECTIONS

In the present incarnation of MoveableMaker, to create a moveable book, one would create a series of individual pages and integrate them within a scrapbook or pre-made book form. For most effects, this does not pose a problem, but for those requiring a cutout on both the Base and Front layers, for example, future iterations of MoveableMaker would need to perform additional constraint checking to identify conflicting designs. While the present work enables the creation of a variety or customizable moveables, the assembled works are limited in that they do not allow for the chaining of output effects, similar to Rube Goldberg machines. The use of simple physics models could allow for multiple effects from a single interaction point or more complex effects composed of multiple linkages or gear chains.

MoveableMaker’s usage of easily accessible materials and technologies (i.e., different types of paper and a hobbyist paper cutter) and support for more complex materials and machinery (i.e., wood or acrylic and a laser cutter), allows mechanical components to be created using multiple methods. With continued advancements and availability of 3D printers, 3D printing could be used to create components such as gears or support and stop pieces. This would support durability and decrease the safety concerns of equipment such as laser cutters.

CONCLUSION

With the ever-growing interest in making and fabrication, there has been increased enthusiasm for tools that empower creation. To this end, we presented MoveableMaker, a novel software tool that assists users in designing, generating, and assembling moveable papercraft. The design of MoveableMaker was informed by a survey of the moveable elements found in a number of children’s books. Our tool integrated many moveable-specific features including constraint-based rendering, animated tooltips, and techniques to support multiple materials and reduce material waste.

The results from preliminary workshops with MoveableMaker illustrated the fun and creativity that can be elicited when making moveables. Participants were enthusiastic about the integration of animated .gifs and MoveableMaker’s potential with children or coworkers. The workshops also highlighted the importance of integrating pre-made physical and digital content and suggested a need for mechanisms to support the sharing of moveable designs.

REFERENCES

1. Baecker, R., Small, I., & Mander, R. (1991). Bringing icons to life. In *Proc. of CHI*, 1-6.
2. Buechley, L., Hendrix, S., & Eisenberg, M. (2009). Paints, paper, and programs: first steps toward the computational sketchbook. In *Proc. of TEI*, 9-12.
3. Coros, S., et al. (2013). Computational Design of Mechanical Characters. *Transactions on Graphics*, 32(4), 83.
4. Esquivela, G., Hartlb, D., & Whittenb, D. (2013). "Pop-Op:" A Kinetic Surface. *Shape Modeling International*, 95.
5. Felton, S., et al. (2014). A method for building self-folding machines. *Science*, 345(6197), 644-646.
6. Glassner, A. (2002). Interactive pop-up card design. 1 and 2. *Computer Graphics and Applications*, 22(1-2).
7. Hendrix, S.L. (2008). PopUp Workshop: Computationally Enhanced Paper Engineering for Children. PhD Thesis, University of Colorado, USA.
8. Hodges, S., et al. (2014). Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In *Proc. of CHI*, 1733-1746.
9. Jacoby, S., & Buechley, L. (2013). Drawing the electric: storytelling with conductive ink. In *Proc. of IDC*, 265-268.
10. Kaihou, T., & Wakita, A. (2013). Electronic origami with the color-changing function. In *Proc. of Smart Material Interfaces*, 7-12.
11. Karr Schmidt, S. (2004). Constructions both Sacred and Profane: Serpents, Angels, and Pointing Fingers in Renaissance Books with Moving Parts. *The Yale University Library Gazette*, 78(3/4), 101-127.
12. Kim, J., & Yeh, T., (2015). Toward 3D-Printed Movable Tactile Pictures for Children with Visual Impairments. In *Proc. of CHI*, 2815-2824.
13. Kim, J., Oh, H., & Yeh, T. (2015). A Study to Empower Children to Design Movable Tactile Pictures for Children with Visual Impairments. In *Proc. of TEI*, 703-708.
14. Kim, J., et al. (2014). Evaluating Tactile User Experience with Tactile Picture Books for Children with Visual Impairment "Touch Me". *Tactile Evaluation Methods Workshop*.
15. Kim, J., et al. (2014). Tactile Picture Books for Young Children with Visual Impairment. In the *Works-in-Progress*.
16. Koizumi, N., et al. (2010). Animated paper: A toolkit for building moving toys. *CIE*, 8(2), 7.
17. Lau, C., et al. (2014). Creating personalized jigsaw puzzles. In *Proc. International Symposium on Non-Photorealistic Animation and Rendering*, 31-39.
18. Li, X.Y., et al. (2011). A geometric study of v-style pop-ups: theories and algorithms. *ACM Transactions on Graphics*, 30(4), 98.
19. Le, S.N., et al. (2014). Surface and contour-preserving origamic architecture paper pop-ups. *Transactions on Visualization and Computer Graphics*, 20(2), 276-288.
20. McGee, L.M., and Charlesworth, R. (1984). Books with movables: More than just novelties. *The Reading Teacher*, 37(9), 853-859.
21. Mellis, D.A., et al. (2013). Microcontrollers as material: crafting circuits with paper, conductive ink, electronic components, and an "untookit". In *Proc. of TEI*, 83-90.
22. Niiyama, R., et al. (2015). Sticky Actuator: Free-Form Planar Actuators for Animated Objects. In *Proc. of TEI*, 77-84.
23. Okamura, S., & Igarashi, T. (2009). An interface for assisting the design and production of pop-up card. In *Proc. of Smart Graphics*, 68-78.
24. Probst, K., et al. (2014). Move-it sticky notes providing active physical feedback through motion. In *Proc. of TEI*, 29-36.
25. Qi, J., & Buechley, L. (2014). Sketching in Circuits: Designing and Building Electronics on Paper. In *Proc. of CHI*, 1713-1721.
26. Qi, J. & Buechley, L. (2010). Electronic popables: exploring paper-based computing through an interactive pop-up book. In *Proc. of TEI*, 121-128.
27. Qi, J. & Buechley, L. (2012). Animating paper using shape memory alloys. In *Proc. of CHI*, 749-752.
28. Ramakers, R., Todi, K., & Luyten, K. (2015). PaperPulse: An Integrated Approach for Embedding Electronics in Paper Designs. In *Proc. of CHI*, 2457-2466.
29. Saakes, D., et al. (2013). PacCam: Material Capture and Interactive 2D Packing for Efficient Material Usage on CNC Cutting Machines. In *Proc. of UIST*, 441-446.
30. Saul, G., Xu, C., & Gross, M.D. (2010). Interactive paper devices: end-user design & fabrication. In *Proc. of TEI*, 205-212.
31. Shigemune, H., et al. (2014). Design of paper mechatronics: Towards a fully printed robot. *Intelligent Robots and Systems*, 536-541.
32. Shorter, M., Rogers, J., & McGhee, J. (2014). Enhancing everyday paper interactions with paper circuits. In *Proc. of DIS*, 39-42.
33. Stangl, A., Kim J., & Yeh T. (2104). 3D Printed Tactile Picture Books for Children with Visual Impairments: A Design Probe. In *Proc. of IDC*, 321-324.
34. Stangl, A., Kim, J., & Yeh, T. (2014). Technology to Support Emergent Literacy Skills in Young Children with Visual Impairments. In *CHI Extended Abstracts*.
35. Strohmeier, P., et al. (2012). A Flock of Birds: bringing paper to life. In *Proc. of TEI*, 333-334.
36. Tsuji, K. & Wakita, A. (2011). Anabiosis: An Interactive Pictorial Art Based on Polychrome Paper Computing. In *Proc. of ACE*, 80.
37. Zhu, K. (2012). A framework for interactive paper-craft system. In *CHI Extended Abstracts*.
38. Zhu, K. & Zhao, S. (2013). AutoGami: a low-cost rapid prototyping toolkit for automated movable paper craft. In *Proc. of CHI*, 661-670.