kidCAD: Digitally Remixing Toys Through Tangible Tools

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ABSTRACT
Children have great facility in the physical world, and can skillfully model in clay and draw expressive illustrations. Traditional digital modeling tools have focused on mouse, keyboard and stylus input. These tools may be complicated and difficult for young users to easily and quickly create exciting designs. We seek to bring physical interaction to digital modeling, to allow users to use existing physical objects as tangible building blocks for new designs. We introduce KidCAD a digital clay interface for children to remix toys. KidCAD allows children to imprint 2.5D shapes from physical objects into their digital models by deforming a malleable gel input device, deForm. Users can mashup existing objects, edit and sculpt or draw new designs on a 2.5D canvas using physical objects, hands and tools as well as 2D touch gestures. We report on a preliminary user study with 13 children, ages 7 to 10, which provides feedback for our design and helps guide future work in tangible modeling for children.

Author Keywords
Tangible Sculpting Tools; Children's Design Tools; Digital Clay

ACM Classification Keywords
H.5.m [Information Interfaces and Presentation (e.g. HCI)]: Miscellaneous;

General Terms
Design, Human Factors

INTRODUCTION
Young children can create expressive artwork with hands and physical tools, by arranging, pressing, molding, and drawing. Psychologists and educators believe that this type of physical interaction and creative play is important for a child's development [20]. However, after kindergarten, in western culture, children are encouraged to ignore play and the physical world in education [25]. The loss of shop class for older children also highlights this trend of pushing children away from physical and manual creation.

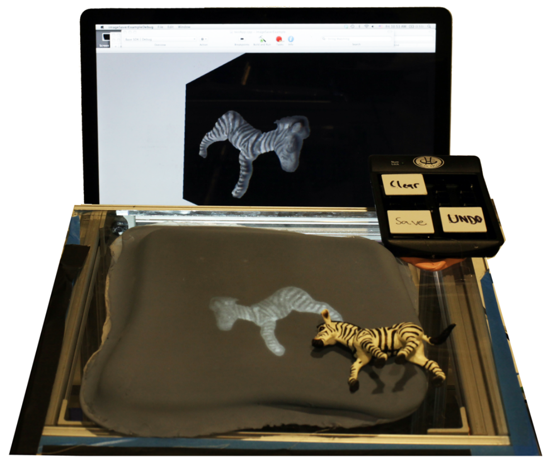
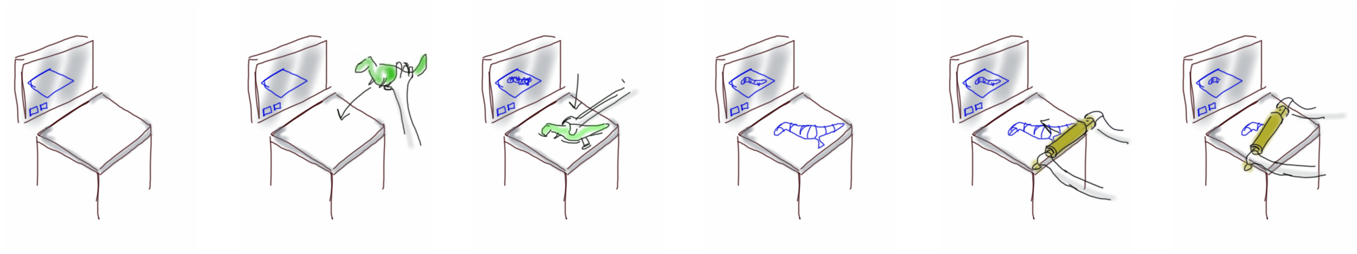


Figure 1: KidCAD system, with deformable gel and co-located project below, and secondary screen with 3D view above. Here a Zebra toy is imprinted, note that the zebra pattern is captured as well.

The decreasing costs of digital fabrication could provide an avenue for children to once again become makers of physical objects and involved in creative physical activity [11]. Digital modeling tools and rapid prototyping machines have the potential to open new doors for children by making abstract concepts concrete [6]. These tools take digital designs and turn them into physical objects. However, these tools tend to rely on mouse and keyboard interaction, and ignore children's facility with the physical world. For children, digital modeling tools lack the flexibly and expressivity afforded by the physical world. We seek to integrate the physical world into digital design. To design modeling tools for children, we wish to create a more clay-like interaction, harnessing skills they already have such as sculpting or drawing. Digital modeling tools for children may not need to focus on sub-milimeter precision, but instead on creativity support, speed and flexibility.

To create more fluid modeling tools for children, we seek to integrate physical interaction by allowing users to use existing physical objects as tangible building blocks for new designs. By allowing children to "copy" from the physical world around them, we hope to expand children's view of what objects are and what they can be; this transformation from viewing an object as just an object, to viewing it as a tool is an important step in expanding creative thinking [12]. A similar ideal is expressed in remix culture, which has rev-



(a) The KidCAD system with an empty canvas.

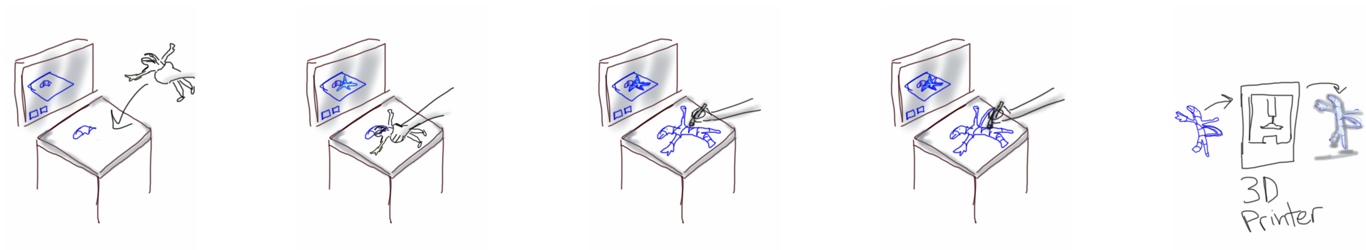
(b) Find a dinosaur toy.

(c) Stamp the dinosaur into KidCAD to copy it.

(d) The dinosaur appears where the child stamped it.

(e) The eraser tool.

(f) Erase the body of the dinosaur.



(g) Find a new doll toy.

(h) Stamp the body of the doll into KidCAD

(i) Pick up the drawing pen tool.

(j) Draw wings on the new toy.

(k) 3D print the final design, to have a new physical toy.

Figure 2: KidCAD Scenario

olutionized content creation in the digital age, and expanded the number of "authors" dramatically [18]. Our belief is that when copying is made easy, copying becomes creation.

This paper explores how we can integrate remix and mashup culture into digital modeling tools, and how to draw on the physical world as a source for these new designs. To accomplish this we integrate the tools for 3D scanning into design tools, speed this process to make capturing a 3D scan instantaneous, and make 3D scanning direct and tangible. This is accomplished through the use of the deForm realtime malleable input device [8]. This provides our users with tangibility, flexibility and speed to create improvised 2.5D forms which can then be materialized through 3D printers.

We introduce KidCAD, a tool for children to remix physical toys through tangible interaction. KidCAD borrows the metaphor of imprinting into clay to copy an object's 2.5D shape and 2D greyscale texture. KidCAD is built on top of the deForm malleable input device, which can scan objects in realtime as they deform its malleable surface. With KidCAD a child can take a toy or object and press it into a deformable screen, where a digital representation of the toy appears in that exact location. "Imprinting" allows for a more direct interaction of copying geometry than traditional copy and paste. Through imprinting, KidCAD can support stamping and sculpting with arbitrary objects and hands. Special tools allow for drawing and erasing. 2D finger gestures allow users to select, rotate and scale. Finally, once the user is done creating an object it can be exported for 3D printing.

This paper presents our background research through an initial low-fidelity prototype exploring the feasibility of a tool for remixing, as well as an overview and implementation details of the final working system. We also present the findings from an initial exploratory user study with 13 children, ages 7 to 10. In the study, children were able to create complex 2.5D models, by combining a number of physical objects as well as drawing and sculpting new parts. Our study also highlights other uses children found for KidCAD including storytelling, illustration and exploring texture and pattern. We describe the limitations of our current system that were uncovered through the trials and highlight possible improvements, but also point towards future work in tangible modeling tools for children.

Scenario

KidCAD was designed to allow children to remix toys, see Figure 2. For example, a child could take a dinosaur toy and stamp it into KidCAD's deformable surface. The dinosaur's 2.5D shape will be copied along with its 2D greyscale texture. The shape will be displayed on the gel surface in an isometric view directly where the dinosaur was stamped down, in addition to a 3D perspective on a secondary context screen. The child could then take the rolling pin tool, which functions as an eraser and roll it over the dinosaur's body and legs, leaving only the head. Next the child could take a doll and stamp its body into the gel surface bellow the dinosaur head. The child will see the body combined with the dinosaur head. Next they can use the pen tool to draw in wings. Finally they can 3D print their new toy and play.

RELATED WORK

Computer Graphics for Children

There have been many Creativity Support Tools designed for children with 3D modeling in mind. More recently there has been a move towards more applied 3D tools for children that focus on fabrication [6]. These tools embrace the constructionist belief that children can learn through doing. There have been tools for children to design wooden automata [2] or pop up books [14]. However, many of these tools currently rely on traditional mouse and keyboard interaction.

Other systems focus on allowing children to create stuffed animals. Plushie, a system based on Teddy, allows users to draw 2D curves to create 3D shapes and print out templates that allow 2D patterns to be sewn into 3D forms once stuffed [19].

Tangible Building Block and Sculpting Systems

Researchers have long worked on bringing tangibility to digital design tools. Early work in tangible design tools focused on computerized building block type systems [1]. These systems allow users to build a model by arranging blocks that may represent walls, doors, or tables, on an electronic base that can actively sense which blocks are placed where. Tangible building block systems can also provide feedback on a variety of different parameters. For example Senspectra allows users to build structures that can be deformed, and the level of deformation on individual vertices is displayed through color LEDs [16].

Researchers have also been working to create design tools for children that support tangible interaction. Posey is a poseable hub and strut construction toy, which allows children to build different models in the physical world and each part's position and orientation is relayed to the computer [27]. A more abstract design tool UCube allows users to create 3D vertices through tangible interaction [17].

One limitation of many of these tangible building block systems is that the user must use only predefined pieces, which often contain electronics or patterns that can easily be tracked by the computer.

Illuminating Clay and SandScape allowed landscape designers to manipulate a physical clay or sand models of landscapes with their hands [21]. These changes in the models were scanned in at 1 Hz using a 3D laser range finder. Projected digital feedback on top of the clay or sand could show the designer simulated water runoff or erosion patterns over time based on the current physical model. In this system the designers are limited to only mirroring the physical sculpture to the digital world, and thus are limited by the constraints of the physical world, for example the lack of an undo function, or loading and saving capabilities.

Other researchers focused on creating malleable or deformable input devices that would modify onscreen graphics, allowing them to have the physicality of input, but the flexibility of digital modification. Tovi Grossman used a bendable curve with embedded flex sensors called Shapetape along with a 3D position tracking of the curve to allow designers to create and modify 3D curves with two hands [13]. Research has also explored deformable materials with embedded sensors to detect deformations [26].

One other approach is to use passive deformable props along with active sensing of 3D hand position to approximate deformations on a 3D object; the tracked hand can press into the foam prop to sculpt onscreen graphics [23]. The passive deformable prop can also be tracked in 3D space and used to squash, stretch, or twist 3D models. The passive deformable prop gives haptic feedback and resistance to the user, mimicking the sensation of deformation.

Remixing and Creativity tools

One thread in computer graphics has been modeling by example, which can allow users to easily design 3D objects based on other 3D objects [9]. Recently more sophisticated tools have used data processing to intelligently suggest what parts and models to add and combine [4].

This concept of design by example and remix has been adopted by a number of tangible interfaces for children, focusing on remix 2D photos or textures with input from the physical world. I/O Brush allows children to paint on a touch screen with colors and textures from the real world, captured by a special brush with an embedded camera [22].

BACKGROUND RESEARCH: REMIXING TOYS

Figure 3: A child's design in Play Doh made by stamping objects and toys.

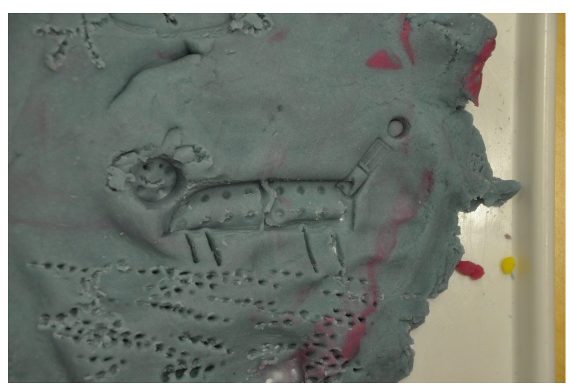


Figure 4: Small details are filled in with a fine pencil on top of stamped designs..

We conducted an initial exploration to investigate if children would be interested in remixing toys and what kind of designs would emerge. As an analog for the interface we would end up designing we used Play Doh. Play Doh is a very malleable sculpting material that young children can easily play with.

We selected children aged seven to ten years as our target audience, and as such found a class of second graders ages seven and eight to participate. Two groups of six children each participated in the study, with a total of 6 girls and 6 boys. Children were split up into two tables, each given approximately one pound of Play Doh to work with. All Play Doh was colored blue, as we only wanted to explore shape and form in this study. During the session the children's task was to create animals by stamping objects into rolled out Play Doh one inch thick. The rolled out Play Doh was intended to be an analog for our remixing interface. A number of toys, blocks, knives, pencils and other objects were laid out for children to use with the clay.

We observed some interesting trends that seemed to be exhibited in a number of children's designs. The most prevalent was the use of stamping to create a patterned texture.

There was often a combination of many different objects in addition to drawing into the clay. Many of the children used over 5 different tools or toys to create their animal. Children seemed quite resourceful in using existing toys or objects to create new designs.

However, almost all designs utilized drawing. Children tended to use existing objects to layout the general shape, and then use drawing to fill in more details. This speaks to the need to support a wide variety of input in future design tools.

Hands tended to be used to clean up mistakes, and erase areas, but were not used as often to create geometry. Although a number of times children used their entire hand as geometry, but there was not as much sculpting with fingers as we had expected to see.

KIDCAD SYSTEM

In designing KidCAD we wanted to create a system that could mirror the flexibility of clay or Play Doh, but with the added value of digital interactions. From our initial background research we found a number of important issues to consider that influenced our design.

From this background research we proposed the following design principles for KidCAD, in addition to those espoused by many other creativity support tools, such as supporting exploration, expressivity and epistemological pluralism [24].

- *Direct Interaction* - We wanted the ease of working directly with clay and having no other distractions. Thus, it was important to have co-located projected feedback at the center of interaction. We also did not want to have any modes, but instead rely on implicit mode changes through tangible tools.
- *1:1 Scale* - Keeping the scale at 1:1, between input and display, would help facilitate the direct interaction, and allow children to very easily create a cognitive model mapping input to output. This helps achieve the goal of creating an interaction similar to clay.
- *Flexible Input* - From the observations in the background research we found that it was important to support many different kinds of input: from drawing and stamping to sculpting and hands-on manipulation of the canvas. The system needed to be fast enough to allow users to stamp shapes quickly when creating texture.

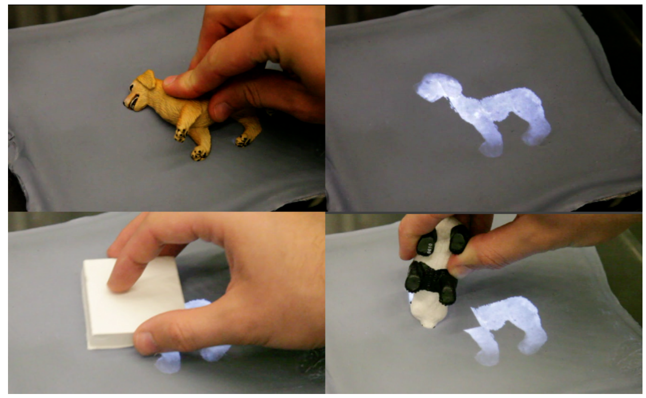


Figure 5: Remixing Toys with KidCAD.

Interactions

KidCAD consists of a malleable gel surface, with co-located projection, which children can press objects, hands and tools into to create and modify 2.5D geometry. This visual feedback is only a top-down view. A secondary screen behind the deForm device provides a rotatable 3D view. A small keypad provides functionality such as undo, save and clear. Interaction into the gel surface adds or modifies 3D geometry, where as 2D touch interaction on the surface modifies their 2D positions and orientations. Tracked tangible tools can be used to draw and erase geometry. The current KidCAD system allows for 2.5D textured depth maps to be created as opposed to full 3D models. For each 2D pixel, we allocate a greyscale color value as well as a depth value. This allows us to directly use the 2.5D depth information to create geometry, and simplifies both the interface and the implementation. Children can make half of an object using our 2.5D system, and later decide if they want the back of the model to be flat, or a mirrored reflection of the front.

Copy and Deform

To copy a physical object's 2.5D geometry and 2D greyscale texture, such as of a toy, a user presses it into the interaction surface where they want it to appear in the digital model or canvas. The deeper the object is pressed the thicker the 3D model will be. The adding of geometry is inverted such that when a user presses into the gel, the shape is added in the positive direction of the digital model. Objects or hands can be used to add geometry to the system. As new geometry is added it builds on top of what other geometry was under it, so that objects can be designed to be much thicker than the 1 inch depth of the gel surface. Each object that is added is segmented and can be independently modified.

Draw and Erase
In addition there is a drawing pen that allows users to draw 2.5D geometry. The height and diameter of drawn geometry is based on the depth of the pen tool in the gel, which is relational to the force applied to the pen. The pen is comprised of a roller ball with a 1 inch diameter and shaft to grip. There are two tools available to erase geometry, a rolling pin and a drawing tool. To erase users roll these tools over the areas they wish to erase. This erases both the 2.5D geometry and the 2D greyscale texture. A rolling pin tool allows users to flatten specific areas the geometry, essentially erasing the area directly under the tool. The amount of flattening is also based on the depth of the rolling pin.

Scale, Rotate, Translate
Touch on the surface, as opposed to into the surface, manipulates existing data. Users can select an object that was copied, or drawn strokes, by touching them with one finger on the interaction surface. Once an object is selected users can translate the object by dragging their finger. To rotate the object users can use two fingers and rotate the fingers. To scale the object users can use a two finger pinching gesture.

Undo
Users can undo added geometry, drawings, erase gestures, and translations by pressing the undo button on a keypad. There is an infinite undo stack, so users can easily go back to earlier designs.

Mirror
The mirror tool allows users to mirror their design about a line of symmetry controlled by the position and angle of a tangible phicon.

Output
Once users have designed a new toy, the geometry can be exported and it can be sent to a 3D printer. Currently the system requires users to load the geometry file into the 3D printer software manually, although in the future we hope to create a turn-key system. We use ZCorp 3D printers to print KidCAD models as they can print in full color or greyscale.

SYSTEM IMPLEMENTATION
The KidCad software is built on top of the deForm sensing platform. deForm is a real-time 2.5d surface interface that uses infrared (IR) structured light scanning and projected visual feedback. deForm combines a passive deformable surface with real-time 2.5D and 2D greyscale texture capture to support a wide variety of input. Instead of directly tracking tools, objects, or hands, our system indirectly senses them through deformations of a highly pliable surface. This approach provides passive haptic feedback, and makes clear to the user where the surface of interaction begins and when objects are being scanned. We use a 1 inch thick gel surface, which is cut into a square measuring 8 by 8 inches. The gel is deformable, but very elastic, and returns to its normal state after the object is removed. The gel is optically transparent and the surface is painted with a gray paint to capture only

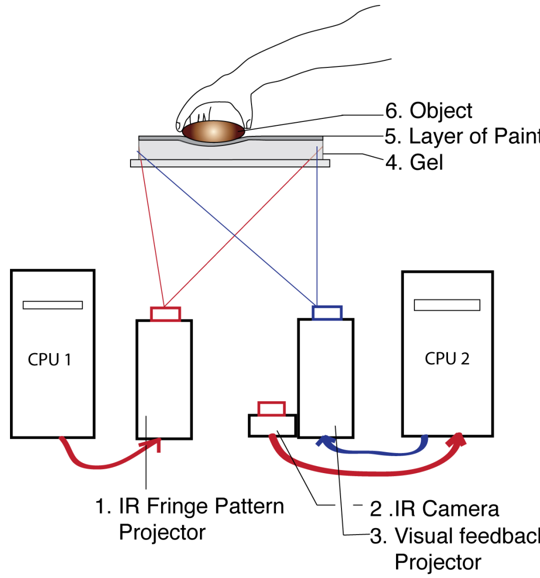


Figure 6: deForm system diagram.

the geometry of the surface of the gel as opposed to objects above the gel. deForm captures and projects from bellow the gel surface, see figure 6. Tools for erasing and mirroring are tracked via capacitve sensing on their handles, which allows us to know which tool is being used.

The kidCad software is written in C++ with OpenFrameworks libraries. We use OpenGL and shaders to display the 2.5D mesh. The software runs on a Apple Mac Book pro from 2009, with a 2.8GHz Core 2 Duo, at 20 frames per second.

Filtering deForm Input
The raw depth information from the deForm sensor is filtered. First, background subtraction is used to detect only relative deformation of the gel surface. Next, the system calculates the overall deformation by summing all of the pixels in the depth map. If the sum is greater than a threshold, the system interprets sensed deformation as user input. We then break up the interaction into sections where an object or multiple objects are deforming the surface. During the time that any object is deforming the surface, we find the maximum depth per pixel over that time, and store it as a greyscale value in a 2D depthmap. Once the object is removed, we add that maximum depth per pixel to the model and preview this to the user as they are deforming it.

Each deformation step is stored as a separate texture. When a user removes an object and stops deforming the surface, a new object is created. The object is represented by two 8bit greyscale images, a depth map and a greyscale texture image. The depth map stores the object geometry as a 2.5D surface. Each pixel value represents the height or the corresponding surface point, ranging from 0 to 2.0 inches. In order to translate, scale or rotate objects through touch our system uses 2D affine image transformations on the the 8bit depth map and the greyscale texture image.

Output

Once the user has chosen to 3D print the new design, a .ply file is made. The .ply file contains a vertex mesh, as well as color values for each vertex. The mesh is generated from the sum of all objects, and is similar to the one used in the display functionality. This .Ply file is then sent to a Zcorp 3D printer. The ZCorp printer can print 3D objects in full color.

USER EVALUATION

We conducted a preliminary in-lab user study in order to evaluate KidCAD and better understand how children use the system. Particularly we were interested in understanding what children would create with KidCAD, what patterns of use would emerge, and what areas to improve upon in further versions. We attempted to frame our observations and analysis around the design principles espoused in the chapter Design Principles for Tools to Support Creative Thinking [24] and suggested in the Creativity Support Tool Index [3]. Of those design principles, we chose to focus on Exploration, Expressiveness and Supporting Many Paths, as we felt they most closely aligned with our design goals.

Thirteen children aged seven to ten years old, eight male and five female, participated in our preliminary study, in single child sessions in a lab based setting. Participants were self selecting and found through an email message sent to a college campus mailing list, which parents of participants responded.

The Sessions lasted 45 to 60 minutes. The study set up included the KidCAD system, a second screen featuring a 3D perspective view of the model, and an assortment of toys and objects children could use with the system, shown in Figure 8. Each study session began with an introduction to the KidCAD system, and an explanation of its features. Next the participant had a warm-up task to get used to the system, and was free to play around for five to twenty minutes. In the second task the participant was asked to create two animals, an elephant and a rhinoceros, using the KidCAD system and the assorted toys and objects, see Figure 7 for a collection of elephants. The final task was for the participant to create a story with a character and design a toy of that character using the system, and then to tell the story to his or her parent. After the session, participants were asked a number of interview questions, pertaining to their experiences with the system. The sessions were video-tapped and later transcribed and analyzed. The designs were not 3D printed in the session due to time constraints associated with 3D printing.

Findings

All children successfully completed our tasks, and many were pleased with their results. Children embraced the idea of "imprinting" shapes into the gel surface very quickly, as well as erasing and drawing new parts. It seemed easy for children to layout 2.5D designs, and there were almost no questions or need for clarification about the interaction. Children also remarked that they liked the feel of the gel. One participant, P13, explained how he liked it because "it was, like, squishy", and how it was "not hard" and that he would want one for his computer. Many explained that it reminded them of clay, and that the softness made it feel more natural.

Initial Use Patterns

One of our goals was to better understand what children would design using KidCAD without our supervision. During the unsupervised first session children were only given instruction on how to use KidCAD, but not on what to do with it. This session provide us with some insight into other uses for KidCAD beyond remixing toys.

One predominant theme we saw was children creating patterns and textures. These compositions allowed children to explore the accuracy of the system, but also seemed very expressive. Patterns were often dominated by repeated stamping of a few different toys, often to form very geometric shapes such as squares or crosses. Often one item would be a central fixture in the piece, and then many repeated items would surround it. Children also explored and played with texture, something that might be difficult with traditional CAD tools. Children created texture scapes through a variety of different means, such as using their hands to imprint little dimples, using their entire arms and elbows to create deeper shapes, or rolling objects to get a repeated pattern.

Another emerging trend was to create pictorial scenes by copying a number of toys in their entirety. Children would imprint characters and also create settings, such as a tent or a tree, by combining multiple objects.

Exploration

We observed participants combining many different objects during the creation of a single model. For example, to design an elephant participants used an average of five different objects, often using these objects multiple times. Participants would often search for the object that fit their needs, and then try a few different locations with it above the gel surface before they pressed it in to copy it. This seemed to highlight the importance of having co-located projected feedback.

In addition, the flexibility of input choices provides users with many means for achieving the same goal. For example, to create a thick 2.5D line we observed children drawing, stamping lego blocks and plastic tubes, or even rotating a lego gear. We also observed children building things out of lego in the physical world and then stamping them to copy the new shape.

When they found that a part they had imprinted did not work as well as they had hoped, participants primarily used the erase tool to delete that part. If there was not that much progress on the model they would often instead just clear the entire canvas. Other users found the clearing function to be liberating, and cited that as a large advantage over clay. One parent discussed with his son, P3, that the ability to clear things very easily, combined with the speed of copying objects enabled him to create many different scenes and test designs quickly.

Expressiveness

As documented in the objects created, see figure 7, users were able to create identifiable objects, and be satisfied with the results. Many of the users felt that the system was very expressive. When asked what she enjoyed about the system, one female participant, P5, remarked, "it was like sculpting

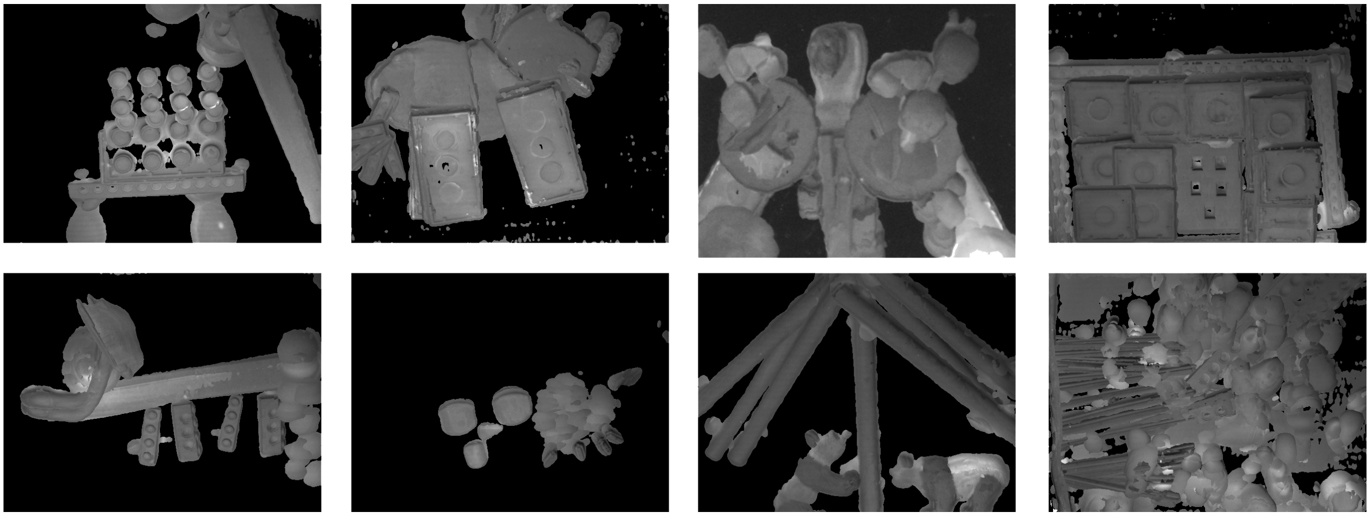


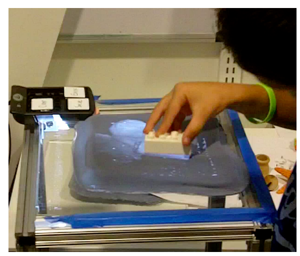
Figure 7: On the left two columns Elephants Designed Using KidCAD. Third Column Top: a Robot, Bottom: Pictorial scene of pandas. Fourth column shows children's explorations in Pattern and Texture.

with clay... I like how accurate it is, when I imprint the shape it is so accurate." She said she would use it at home to sculpt things instead of using clay. And users displayed a great deal of finesse while using the system: they were able to imprint portions of objects easily, as opposed to the entire object and seemed quite capable at combining objects together. Some users felt KidCAD would help them accomplish creative tasks that would have been difficult naturally. One user, P11, explained it could help people "draw something in 3D, if they weren't so good at drawing in 3D." Another thought that it was "easier than sculpting with clay. You don't have to cut it and wet the two parts to get them to stick together."

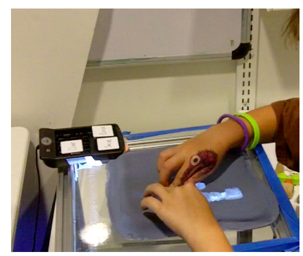
However, other participants found the system somewhat lacking in accuracy. One participant felt that it was better suited for roughing out shapes and then he would need to use something else later to get more detail. P3 added, "probably I could use the things I already have to make imprints of maybe a rough draft, of sort of the basic idea of what it would look like, but not all of the details." To him the pen tool did not provide enough accuracy to add the detail he wanted. P1 felt that it was difficult to use KidCAD to always "get exactly what you want" but that KidCAD was still useful because it allowed you to take more time and easily change things. Others missed the ability to fully feel the object they were creating, one user explaining that with clay you could "actually feel them."

Most children created fully fleshed out figures with 2.5D depth. However one child created designs that only consisted of outlines. This difference between line drawing and sculpting was also noted by some participants. One participant explained that kidCAD was like drawing but "its not lines" and that "it like absorbs [what you press in]."

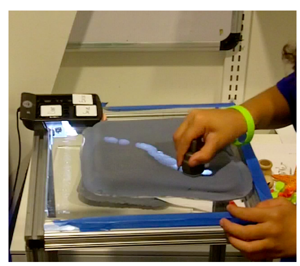
When participants did try to create full 3D structures they found the tools lacking, due to the limitations of 2.5D. One participant, P2, tried for around six minutes to create a DNA double helix with overlapping strands. The participant was



(a) Stampers



(b) Sculptors



(c) Sketchers

(d) Some items used with KidCAD

Figure 8: a-c. Different ways of interacting with KidCAD. d. Some items provided for to children use as tools.

unsatisfied with the fact that he could not create empty space between two of the strands when they overlapped. This seemed to highlight the limitations of 2.5D geometry vs true 3D geometry.

Supporting Many Paths

We observed many different styles of use during the KidCAD trials, however for the most part they fell into three categories: "stampers", "sculptors" and "sketchers".

"Stampers" used KidCAD along the lines that we had created the system. These participants mostly used existing object, and copied them by stamping them down into KidCAD. They also used the drawing tool and erasing tool, as well as using their hands, but for the most part they were remixing existing objects.

"Sculptors" instead focused on using their hands or other tools to sculpt a 3D form. Even if they used objects, for the most part they were not copying the shape, but instead using it to deform the 2.5D geometry. These children treated the gel surface very closely to how one would sculpt with clay, often repeating the same basic path with their fingers or other tools to create more depth. One participant, P5, explained that the gel had a very similar feel to it to clay and that she liked the deformability. These users also seemed more concerned with the 3D form than many of the others, and looked at the 3D perspective view more.

The third group, "Sketchers," primarily used the drawing tool. They did not concern themselves with the 2.5D view and treated the canvas very pictographically. They created much of the content themselves and were less focused on remixing objects. P3 for example explained that he would use it for "exactly what I was doing, to make drawings for a story... like if I was telling a story to someone I would use this to make illustrations of what it would look like."

Storytelling with KidCAD

The last task of the study encouraged participants to come up with a story and then design a toy using KidCAD of the main character of that story. Most of the participants came up with stories around their characters, but only designed the single main character. However, we were also surprised to see other participants use KidCAD as an illustrative canvas. Participant P3 used the flat work area of KidCAD as a 2D canvas to have characters interact on, and created 7 sequential scenes. One interesting observation was that by including whole existing toys in the story as characters, children could easily create many different scenes very quickly, by simply stamping them down where they wanted the character to appear in that scene.

3D Printing

Although we were unable to 3D print the participants models during the session due to time constraints, in post test interviews we discussed the concept. All of the participants in the post-test interview answered that they would want to keep a 3D printed copy of at least one of the objects they created. When asked what they would make with KidCAD if they could 3D print the results, participants had a number of different ideas. One wanted to use it to "make a little present for someone", another for "making a movie" or copying their friend's toy that they really liked. However the concept of 3D scanning and printing, and its limitations, was still complicated for some children to understand. For example one participant wanted to copy a DVD and 3D print a new copy.

DISCUSSION

Children found that it easy to copy geometry from physical objects using KidCAD and it was also clear to them what parts of the objects they were copying. One participant, P11, explained, she could "put 3D shapes on a rubber pad to make the same 3D shapes on the computer." Because the act of copying was embodied in the imprinting gesture children did not seem to perceive or talk about different modes, or the independent act of 3D scanning. It was clear to the users what the results should be because the deformation was an embodied process. It was also easy for the users to copy only parts of objects by only pressing those parts in, something that would be complicated with traditional 3D scanners. The inverted nature of imprinting to add material did not seem to bother children.

Children seemed to be able to use KidCAD to remix objects through tangible imprinting very easily. One participant P8 identified this type of remix and enjoyed it, explaining her favorite part of KidCAD was that "you could turn every day things into a whole new idea." The advantage of using physical objects to design is speed, you don't have to make everything from scratch, but also that you can be inspired by the objects around you and create "new ideas" or designs that could be hard to think of. We believe that by grounding KidCAD in the physical world, it can help children to think about the process of design. The physicality and simplicity of creating geometry through stamping, sculpting and drawing allows children to get further much quicker that with traditional digital modeling tools. And, in contrast to the physical world, children can easily create new toys with this system, without destroying or taking apart current ones.

Comparing the results of the of the user study with KidCAD to our initial user exploration with clay, we found children often used KidCAD in very similar ways to the clay experiments. Users of KidCAD relied less on drawing and created more sculptural forms, and were less reliant on thin lines. However KidCAD users did not frequently scale, rotate or move individual parts, instead focused on stamping techniques also observed with the clay experiments. Children however seemed to be able to more quickly explore alternatives, and more easily undo things with KidCAD. We observed children spend a longer time on individual designs with clay than with KidCAD, and more designs were explored with KidCAD when controlling for time. We believe further work could push KidCAD's modeling abilities further, especially beyond 2.5D sculpting.

In someways KidCAD is similar to existing building block type tangible interfaces. Users combine existing objects to create something new. However, we believe that KidCAD highlights a different type of design that is more improvisational. Instead of a fixed set of items that can be combined, KidCAD allows any physical object to be easily combined with other objects, in the digital world.

We hope that this type of improvisational design can bring children back into the golden age of drawing or creativity described by Gardner [10], that many leave after age seven. Instead of seeing the world the way it is, KidCAD encourages children to see objects in the world as tools to get what they want. Csikszentmihalyi explains that "every time we interact with an object the possibility of new learning is potentially there" and that artists and creative thinkers change their perception to see beyond what objects are "supposed" to mean [5]. KidCAD can also allow children to design with personal objects and many children reported that they had many objects at home they would like to use with KidCAD. Many physical objects can hold much more meaning and emotion than simply ink or clay, such as a shell you found on the beach. With KidCAD children can begin to explore expressing those meanings in new ways.

We observed that the 2.5D canvas has an effect on the way that children design and interact with KidCAD. The 2.5D canvas seemed to share more with the 2D page than with the full 3D space of traditional modeling. Children would layout scenes with many characters and a setting such as a tree, or a house. We did not originally envision this type of pictorial use, but it was an interesting emergent behavior. This could be due to a number of factors: Children are more used to the world of drawing, the 2D projection on the flat gel surface, and that relief sculptures historically have been more pictorial. Although we did not design KidCAD for all of these different patterns they seemed to be well-liked by those who used them, regardless of which pattern they primarily used. All of these different paradigms are afforded to the user because of the wide variety of input supported by KidCAD. In addition there is no need for mode changes, instead users simply pick up different tools. It is easy for children to change styles quickly from one design to the next. This highlights the flexibility of KidCAD which in many ways mirrors that of clay; there are endless opportunities to modify clay, no one style is correct.

KidCAD focuses on tangible input, but not fully embodied interaction [7]. The system represents a hybrid approach with tangible, realtime 3D input but only realtime, co-located 2D output. Because of the co-located feedback children can engage in epistemic action [15], and we observed this type of interaction in our study. However, we found that in some cases children desired to have the physical object before it was 3D printed. They could not move or play with design until it is 3D printed, unlike the physical toys they used to design the object. Full 3D embodiment provides a great deal of advantages. However it is limited by the difficulty of computationally changing the physical model. For example, Sandscape stores the model in the physical world, therefore it is hard to computationally change the model. Because of its reliance on projected feedback on a 2D surface, KidCAD can easily change the model computationally, allowing for undo scale, reflection, etc. which are easy to implement in the digital world. We believe a hybrid approach, tangible input and co-located projected feedback, is more flexible and may come to be a more dominate method than fully embodied tangible design tools.

But it is not enough to merely replicate the fluidity and texture of clay sculpting and transport it to the digital, we need to consider how to provide the advantages of digital computation to these tools. KidCAD begins to scratch at some possibilities while remaining close to clay. We believe future work can push this boundary even further, while maintaing the ease and flexibility of interacting with clay.

We are currently in the planning stages of collaborating with an after-school arts program to do a longitudinal study with a whole class of children. This multi-week study will be useful for eliminating novelty bias, but is also more practical as the timescale for 3D printing is still quite slow. This will help us better understand how children would actually use KidCAD to make meaningful objects.

LIMITATIONS AND FUTURE WORK

From our user studys we found a number of limitations with the current KidCAD system which point toward further exploration. One limitation is that the deForm system only allows for interaction with 3D graphics on a 2D screen. Head tracking or stereoscopic glasses could be used to present a 3D view to users. But this does not solve the problem of not being able to touch and feel the 3D models. Our current system relies on elastic gel for only passive haptic feedback. Other mediums with different levels of elasticity could be explored, such as clay. A material with a computationally controlled stiffness could move towards active haptic feedback. Or actuated shape displays could be used to support full tangible 2.5D interaction, although at a high cost.

Children also suggested that we add color to the system. Currently the deform system only supports greyscale capture of 2D textures because it captures in the IR spectrum. However this could be modified to capture in color, and the underlying structured light scanning technology can capture full color 2.5D geometry [28].

Most existing physical objects were never designed to be remixed. However by creating a digital copy, through 3D scanning, we can more easily combine different objects together. But one limitation is that these objects may not have a shared design language. We think there is certainly much future work to be done on elegantly combing or remixing objects, and mixing design languages.

Although this paper details remixing with physical objects, we think there is a rich space for combing physical objects with existing digital models. This would allow children to remix objects that they don't physically own, in addition to ones that they do. Online websites for storing 3D models are becoming prevalent, such as thingaverse.com and google 3D warehouse, and researchers are exploring how to allow users to easily combine these models [4]. By integrating these online databases users could share their designs more freely.

There is a limited set of objects that can be used with KidCAD because of its reliance on the deForm input device. Larger objects, or full 3D objects cannot be captured because of the size restrictions of the sensing area. Future work could explore using depth sensing cameras, such as the Microsoft Kinect, to capture objects at any scale. This type of system would lose the directness of copying with KidCAD, but could be more flexible. In addition we believe there are great opportunities in exploring the move from 2.5D to full 3D interactions in tangible sculpting applications, as other work has shown [23].

A bigger challenge is getting young children to grasp 3D modeling concepts, and striking a balance between ease of use and complexity can be a challenge. A smaller step could be an interface to allow children to tangibly place arbitrary 2.5D models in a 3D scene, as opposed to a 2.5D scene. This could be useful for storytelling and an animation element could be combined.

CONCLUSION

KidCAD provides an easy way for children to create 2.5D models. KidCAD harness a tangible and embodied method for easily copying geometry from existing physical objects and placing it on 2.5D model, which helps users explore many alternative designs. Participants in our user study used many objects along with drawing and hand sculpting to create their designs. Many patterns of use emerged, primarily "Stamping," "Sculpting," and "Drawing." Children successfully remixed objects to create new expressive designs with little training. KidCAD points towards more physical and material CAD interfaces for children, while preserving digital computation and modification of models, and towards CAD tools that embraces remix culture.

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