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Invited Paper

A Brush With Words

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Abstract: We describe a three-way collaboration to build a sculpture that features computational origami through a strip folding font, algorithmically computed word ladders, curved-crease folding, and hand-blown glass.

Keywords: origami, folding, curved creases, fonts, sculpture

1. Introduction

In 2024, we designed and made a paper and glass sculpture called "Brush With Words", shown in Fig. 2. The primary component of this piece is a hand-blown glass brush, measuring 1.5 meters (5 feet) in length and weighing approximately 16 kilograms (35 pounds). The base of the brush is filled with red paper, folded along curved creases. The bristles of the brush are the same red paper, laser-cut into 1 centimeter (0.4 inch) strips. Out of the brush comes what appears to be a single strip of paper that is folded into the words "BRUSH WITH WORDS" (the title of the piece). On the same pedestal, another single strip of paper appears to be folded into text that forms a "word ladder" where each English word differs from the previous by a single letter:

0. BRUSH
↓ *remove R*
1. BUSH
↓ *change H to Y*
2. BUSY
↓ *remove S*
3. BUY
↓ *change U to A*
4. BAY
↓ *change B to W*
5. WAY
↓ *change Y to R*
6. WAR
↓ *add D*
7. WARD
↓ *change A to O*
8. WORD
↓ *add S*
9. WORDS

The concept of the piece is that this giant calligraphic brush uses the folded paper as its magical "ink". As the brush strokes the canvas, the paper ink emerges and folds itself into text according to the user's desires.

The actual execution of the piece required an unusual mix of algorithms, computational origami, curved-crease folding, and glass blowing. In this paper, we describe these various components and how they fit together.

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2. Genesis

The origin of our concept for the piece was an invitation to exhibit in a show called "The Book as Sculpture" at *The Brush Gallery & Studios* in Lowell, Massachusetts, USA (April and May 2024). During an initial site visit, we brainstormed ways to combine our collective shared interests in sculpture, in particular Mariel's expertise as a glass artist and the Demaines' expertise in computational origami. The name of the gallery inspired us to think about brushes, and we drew the initial concept sketch shown in Fig. 1.

Fig. 1: Original concept sketch for "Brush With Words". © Mariel Bass, Erik Demaine, Martin Demaine.

3. Glass

We start with the physically largest components: the two glass pieces that compose the brush. In preparation, we examined several real-world brushes and measured their proportions. Then Mariel blew the glass forms at the MIT Glass Lab, assisted by director Peter Houk. The larger piece, the *handle* of the brush, was sized to barely fit into the glory hole where we reheat the glass for further shaping. The

Fig. 2: "Brush With Words" by Mariel Bass, Erik Demaine, and Martin Demaine, April 2024. Hand-blown glass, silver foil, and Canson Mi-Teintes paper. © Mariel Bass, Erik Demaine, Martin Demaine.

smaller piece, the *ferrule* of the brush, was designed to fit snugly against the handle, and be foiled in silver to give it a metallic appearance.

Fig. 3 shows the tail end of the glass blowing process of the handle, giving a sense of scale.

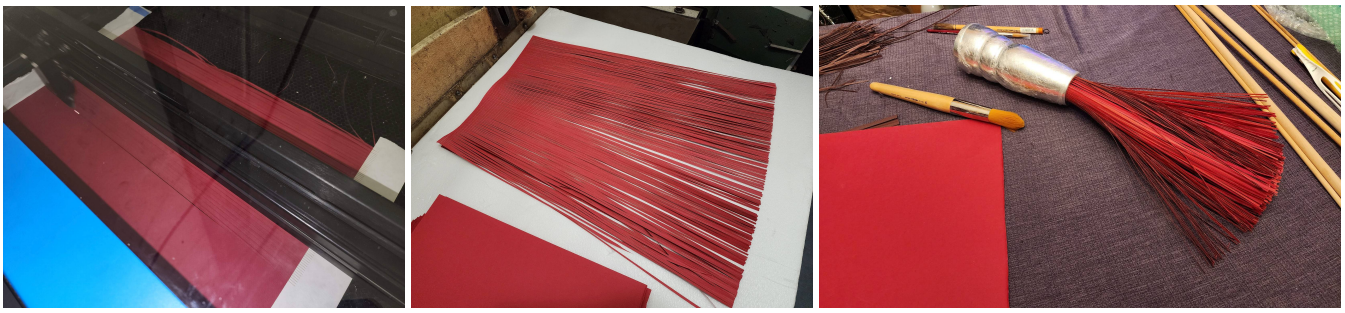
Next, we laser-cut red Canson Mi-Teintes paper into precise 1 cm strips to form the bristles of the brush. Fig. 4 illustrates this process.

Finally, we glued the two parts of the glass brush together. We used HXTAL NYL-1 epoxy adhesive, which fully cures over a period of seven days. Fig. 5 shows our ad-hoc scaffold that held the two pieces in place while the adhesive cured.

Fig. 3: Mariel giving the glass brush handle a final torch. © Mariel Bass, Erik Demaine, Martin Demaine.

4. Strip Folding Font

In 2017, the Demaines developed a font for folding any letter of the English alphabet from a strip of paper [1, 2]. This font was part of a project to show that a horizontal strip of paper with vertical and diagonal creases can fold



(a) Laser cutting (b) Resulting paper bristles (c) Completed ferrule with bristles (and model brush)

Fig. 4: The process of creating the brush's paper bristles. © Mariel Bass, Erik Demaine, Martin Demaine.

Fig. 5: Scaffold holding the glass handle and ferrule together while the adhesive cures. © Mariel Bass, Erik Demaine, Martin Demaine.

universally into any grid polyhedron [2], a result that we recently simplified and improved to also specify the desired number of layers [3].

Fig. 6 shows the font's folding of each letter in isolation. The font also defines how to transition between letters so that multiple words and even multiple lines of text can be folded from a single strip of paper.

We already had open-source software [1] to generate the crease pattern needed to fold the desired text. For this project, we extended this software to design a practical way to make the crease pattern from a square of paper, which involves slitting the paper and folding it into one very long effective strip. Fig. 7 shows the crease pattern and resulting folding of the text "BRUSH WITH WORDS".

5. Word Ladders

The next question was, other than the title "BRUSH WITH WORDS", what text should we write with the brush? Given the complexity of folding words and the limited size of our canvas (poster board measuring 81 × 71 centimeters or

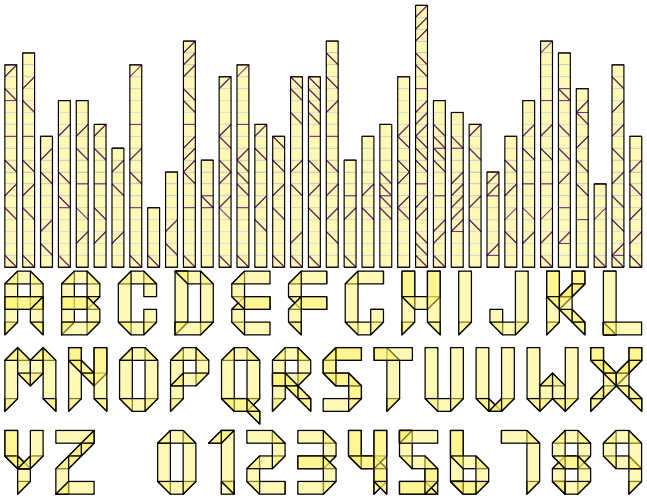


Fig. 6: Crease patterns and resulting folded letters in the strip folding font, from [2, Figure 2]. © Erik Demaine and Martin Demaine.

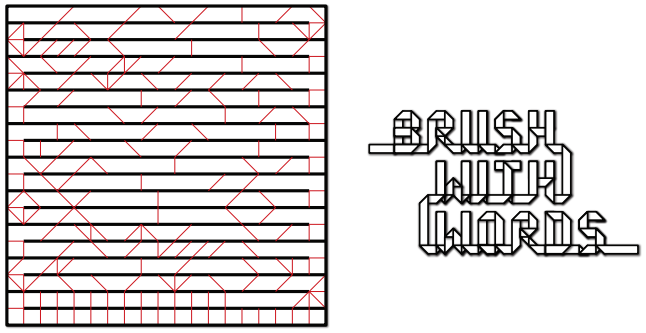


Fig. 7: Crease pattern (left) and resulting folding (right) for the text "BRUSH WITH WORDS", generated by [1]. © Mariel Bass, Erik Demaine, Martin Demaine.

32×28 inches), we wanted to express concepts with relatively few words. We chose word ladders, which also highlight the single-strip nature of the folding.

A ***word ladder*** is a sequence of words in the language (English in our case) where consecutive words differ by a single letter. Word ladders were invented by Lewis Carroll [4], who designed them as word puzzles called "doublets". Five-letter word ladders were studied computationally by Donald Knuth [5].

In most word ladders, the words all have the same length,

and the operation from one word to the next is substituting a single letter. Unfortunately, using a dictionary of the 10,000 most common English words, we found that "BRUSH" and "WORDS" have no word ladder despite having the same number of letters. Thus we extended the rules of word ladders to include adding or removing a single letter, while resulting in a valid word.

Given a set of rules like this, we can define a graph on the words in the dictionary, where vertices represent words and edges represent valid single transformations in the word ladder. It is then a simple matter of breadth-first search to find the shortest ladder from one word to another. Our word-ladder generation and exploration software is open source [6]. In addition to finding the shortest path, it offers a way to explore nearby word ladders by choosing a deviation for the path, or by forbidding undesired words.

In particular, our software found that the nine-step word ladder given in Section 1 is the shortest path from "BRUSH" to "WORDS" using that dictionary. Fig. 8 shows the crease pattern and resulting folding for the strip folding font applied to this word ladder. Fig. 9 shows the result of hand-folding this pattern, as it appears in the sculpture.

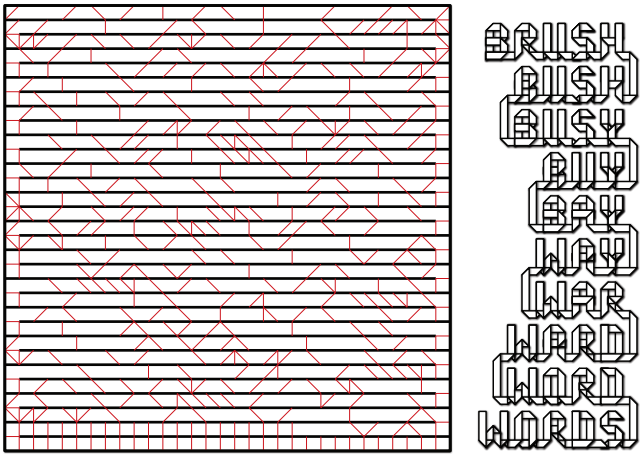


Fig. 8: Crease pattern (left) and resulting folding (right) for the word ladder from Section 1, generated by [1]. © Mariel Bass, Erik Demaine, Martin Demaine.

As an aside, we later tried a larger dictionary of 370,000 English words, and found some interesting word ladders that use only five-letter words. The shortest word ladder is seven steps: BRUSH → GRUSH → GRUSS → GRASS → GRADS → GOADS → WOADS → WORDS. But it involves some obscure words. A longer word ladder using more common words is eight steps: BRUSH → BRASH → BRASS → GRASS → GRADS → GOADS → LOADS → LORDS → WORDS.

6. Curved Creases

The Demaines have a significant body of artwork [7] involving folding paper along concentric circular creases, alternating mountain and valley — a design that goes back to Josef Albers at the Bauhaus in the late 1920s. Some of this work inserts such folded paper into blown glass vessels, where it expands like a ship in a bottle [7].

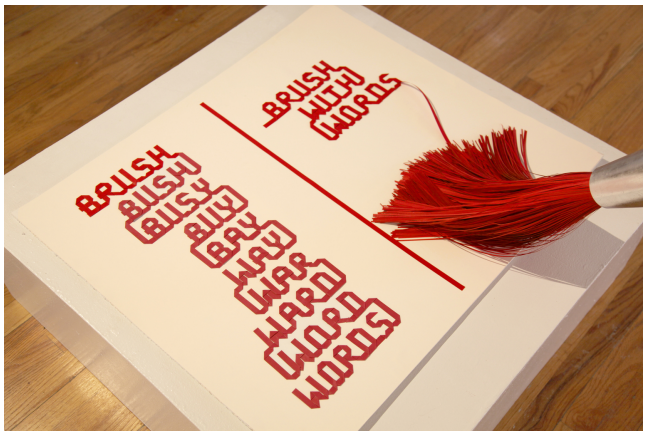


Fig. 9: Detail of "Brush With Words" showing the text from the strip folding font. © Mariel Bass, Erik Demaine, Martin Demaine.

So a natural first step was to fold the same red Canson Mi-Teintes paper we used for the brush bristles, and insert it into the brush handle. (This step of course happened before the two glass pieces were glued together.) This process proved more difficult than usual given the extremely long length of the brush. We ended up using very long chopsticks to reach deep inside the glass, as shown in Fig. 10. Fig. 11 shows a close-up of the final result in the sculpture.

Fig. 10: Inserting curved-crease sculpture into the brush handle. © Mariel Bass, Erik Demaine, Martin Demaine.

To further explore the word ladder theme, we designed a longer word ladder that connects broader themes surrounding BRUSH and WORDS — transitioning PAINT into BRUSH, then BRUSH into WORDS, and finally WORDS into BOOKS. Then we visualized the word ladder as if it were folded from a strip of paper, resulting in Fig. 12.

Finally, we transformed this word ladder into curved-crease sculpture. We printed the word ladder from Fig. 12 onto sheets of white Canson Mi-Teintes paper, imagining that the magical red ink had already set into the paper. Then we folded this paper along concentric circular creases,

Fig. 11: Detail of "Brush With Words" showing the inserted curved-crease sculpture and the crimped ferrule. © Mariel Bass, Erik Demaine, Martin Demaine.

Fig. 12: Larger word-ladder design for the curved-creased sculpture in Fig. 13. © Mariel Bass, Erik Demaine, Martin Demaine.

and combined several pieces to form the two sculptures in Fig. 13. (They can also be seen in the background of Fig. 2.)

7. Conclusion

We hope you enjoyed this short tour as much as we enjoyed the journey of making "Brush With Words". See the webpage https://erikdemaine.org/curved/Brush/ for more photographs of this project. We also encourage the reader to play with our open-source software tools to make their own word ladders [6] and strip foldings [1].

(a) [0721] "Brush Fire" by Erik Demaine and Martin Demaine

(b) Detail of [0721] "Brush Fire"

(c) [0722] "Brush Wood" by Erik Demaine and Martin Demaine

Fig. 13: Curved-creased sculpture folded from the word-ladder design in Fig. 12. © Erik Demaine and Martin Demaine.

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Mariel Bass studied fine art and glass at Massachusetts College of Art, where she first discovered the art of glass blowing and earned a bachelor of fine art degree in 2005. She has attended workshops at well-known craft schools throughout the U.S., such as Pilchuck in Washington, Haystack School of Crafts in Maine, and Corning Glass in New York. She worked for several glass studios in the New England area before relocating to St. John, USVI, in 2008 where she ran a recycled hot glass studio. From 2013 to 2020, Mariel lived in St. Petersburg, Florida, where she operated a large hot glass facility and created blown and sculpted glass for the artist Duncan McClellan, while also continuing to expand her own creative practice. In 2020, Mariel relocated to the New England area where she is originally from. She is currently an instructor at the MIT Glass Lab in Cambridge, Massachusetts, and continues to create one of a kind sculpture in glass and metal for artists, galleries, museums, and private/public commission.

Erik D. Demaine received a B.Sc. degree from Dalhousie University in 1995, and M.Math. and Ph.D. degrees from University of Waterloo in 1996 and 2001, respectively. Since 2001, he has been a professor in computer science at the Massachusetts Institute of Technology. His research interests range throughout algorithms, from data structures for improving web searches to the geometry of understanding how proteins fold to the computational difficulty of playing games. In 2003, he received a MacArthur Fellowship as a "computational geometer tackling and solving difficult problems related to folding and bending—moving readily between the theoretical and the playful, with a keen eye to revealing the former in the latter". He cowrote a book about the theory of folding, together with Joseph O'Rourke (*Geometric Folding Algorithms*, 2007), and a book about the computational complexity of games, together with Robert Hearn (*Games, Puzzles, and Computation*, 2009).

Martin L. Demaine is an artist and mathematician. He started the first private hot glass studio in Canada and has been called the father of Canadian glass. Since 2005, he has been the Angelika and Barton Weller Artist-in-Residence at the Massachusetts Institute of Technology. Both Martin and Erik work together in paper, glass, and other material. They use their exploration in sculpture to help visualize and understand unsolved problems in mathematics, and their scientific abilities to inspire new art forms. Their artistic work includes curved origami sculptures in the permanent collections of the Museum of Modern Art (MoMA) in New York, and the Renwick Gallery in the Smithsonian. Their scientific work includes over 100 published joint papers, including several about combining mathematics and art.