Exploring Shape Designs for Soft Robotics and Users' Associations with Them

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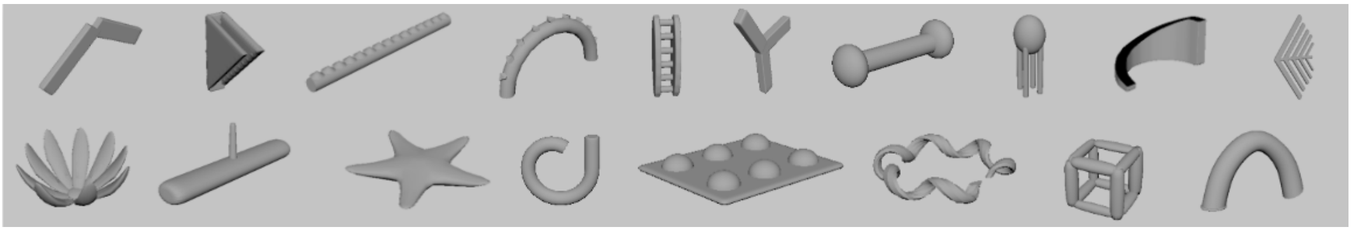

Figure 1: We generated ideas for soft robotics shapes in brainstorming sessions with users. The results were 3D-designed and simulated to be tested in a follow-up user study. This image shows a selection of those shape designs.

ABSTRACT

Soft robotics provides flexible structures and materials that move in natural and organic ways. They facilitate creating safe and tolerant mechanisms for human–machine interaction. This makes soft robotics attractive for tasks that rigid robots are unable to carry out. Users may also display a higher acceptance of soft robots compared to rigid robots because their natural way of movement helps users to relate to scenarios they know from everyday life, making the interaction with the soft robot feel more intuitive. However, the variety of soft robotics shape designs, and how to integrate them into applications, have not been explored fully yet. In a user study, we investigated users' associations and ideas for application areas for 36 soft robotics shape designs, brainstormed with users beforehand. We derived first design recommendations for soft robotics designs such as clear signifiers indicating the possible motion.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **User studies**; **Empirical studies in HCI**.

KEYWORDS

Soft Robotics, Shape Design, Soft Robotics Application, Human Associations, Movement Effects

ACM Reference Format:
Anke Brocker, Ekaterina Nedorubkova, Simon Voelker, and Jan Borchers. 2023. Exploring Shape Designs for Soft Robotics and Users' Associations with Them. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA '23), April 23–28, 2023, Hamburg, Germany.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3544549.3585606

1 INTRODUCTION

Soft robotics offers the design and manufacturing of flexible, highly adaptive mechanisms [24] to provide powerful yet careful interaction with other objects. Design approaches for soft robotics are inspired by biological organisms [11], and often mimic the appearance and behavior of living organisms [6], such as the human body or animals [21]. The essential part of a soft robot is its soft actuator made of a compliant material that transfers the power received into movement [6]. Actuators are most commonly made from silicone, hydrogels, fabrics, and braided materials [3]. Through an actuation mechanism such as a water supply, air supply [13], embedded threads, or magnetic stimulation [18], soft robots receive the power to create their motion with.

Although soft robots already provide the described features, their potential has not fully been explored yet. In comparison to rigid robots, soft robots provide naturalistic, flexible [7], and lifelike movements that users associate with things they know from everyday life. Rigid robots usually include visible joints, hinges, or motors, making them look like machines instead of natural organisms when moving. Soft robotics creates systems that are more tolerant and safer for human-machine interaction than rigid robots [6, 9]. This can lead to higher acceptance of soft robots when including them in usage scenarios. Shape designs associated with

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CHI EA '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9422-2/23/04.
https://doi.org/10.1145/3544549.3585606

real-world objects may help users to interact intuitively with soft robotics interfaces. For example, wearable soft robots are able to create subtle and silent communication with other humans. However, integrating soft robots into various scenarios requires intelligent and flexible designs of their shape. The soft robotics design pool for shapes and their shape changes still leaves room for improvement, and before interesting soft robotic interfaces and experiences can be built, we need to increase the shape variety and understand in which contexts users may accept soft robots. In this paper, we aim for two things: First, we focus on investigating design ideas for soft robots. Those designs involve challenges such as the limitation of size if no strong skeleton structure is present, and being limited in movement speed due to high deformability [10]. Secondly, we aim to understand what users associate with the movements of soft robots, and what applications they can imagine a soft robot in. With these limitations in mind, we intend to open up the discussion of how soft robot designs can be applied within HCI to create novel user experiences and interactive systems. Thus, our contributions in this paper are:

- An overview of design ideas for soft robots collected with users;
- A user study investigating what users associate with these soft robots and what the robots signify to users.

2 RELATED WORK

Due to their unique characteristics, soft robots have become increasingly relevant for the design of novel applications and interfaces in HCI. This section presents application areas and empirical research regarding soft robotics and related shape-changing interfaces.

2.1 Soft Robotics Application Areas

Among the areas in which soft robots can be more suitable than rigid ones, wearable devices, medicine, and smart textures have been identified as particularly salient domains.

Due to the adaptability of their materials, soft robots are capable of interacting with the human body safely [1]. Wearable soft robotics devices often have assistive purposes. For example, a soft robotics assistive glove for people with hand functioning problems can enhance the natural ability of the user's fingers when grasping objects [28]. Along a similar vein, Awad et al. created an exo-suit to assist users in walking [2].

The materials soft robots consist of can be chosen to be safe for human beings and animals. Hence, they can be components for tools used in surgeries and for endoscopic screening [27]. The attachment of soft robots to internal organs still has many drawbacks and limitations. Nevertheless, the abilities of soft robots in this field are very promising. For example Payne, et al. [26] developed an implantable soft robotics system for supporting human heart activity. Placed around the heart, it assists the heart when contracting and relaxing to control blood inflow.

Soft robots can also function as decorative elements in fashion, such as smart fabrics that elongate and shrink clothes, or allow clothes to adapt to a body shape [17]. The ability to change the appearance of clothes dynamically, however, is not the only way fashion can be inspired by soft robots. Clothes with built-in soft robotic actuators may also work as artificial muscles [15]. Scarfy, an interactive scarf [25], and ShapeTex, a shape-changing fabric [8], are textiles and fabrics that can be actuated in order to, e.g., adapt the wearer's look to their emotion or intent. Fabrication of those fabrics requires many time-consuming steps; therefore, Miller-Jackson et al. worked on a method to enhance fabrication reliability and simplify the whole process of fabrication [16].

2.2 Understanding Soft Robotics Interfaces

Despite the fact that application areas of soft robots are continuously growing, there are limitations and challenges. In HCI, soft robots belong to the research field of shape-changing interfaces. Qamar et al. [19] present a recent review of shape-changing interfaces in HCI, and of how shape-changing techniques have evolved. Brocker et al. [4] discuss the relevance and challenges of programmable matter, actuated materials, and soft robotics in HCI in particular. Twelve design challenges of shape-changing interfaces are discussed by Alexander et al. [1]. Of those twelve, the following challenges of shape-changing interfaces are relevant in particular to soft robotics actuator designs: First, the design space of soft robot movements is still rather limited. Second, there is a large gap between how researchers and designers intend soft robots to move, and how they act in practice [14].

Understanding the effects of soft robots motions is important for designing novel user interfaces. Strohmeier et al. [23] investigated whether participants are able to express and identify emotions using a shape-changing interface. In the first experiment, participants expressed various emotions (contentment, delight, happiness, sadness, and love) by deforming a flexible 2D sensor. In the second experiment, these deformed shapes were designed as animated 3D models and another group of participants had to identify these emotions (33,8% were correctly identified). This shows that it is quite challenging to design shape-changing objects that signify universal information.

Rassmussen et al. [20] conducted a study in which participants were asked to draw sketches for shape-changing interfaces that either shows a radio or a mobile phone. The results show interesting elements and metaphors to design those interfaces, but also underline that the vocabulary for sketching such interfaces needs further development.

Kim et al. 2018 built shape-changing interfaces design taxonomies based on reconfigurable objects that participants use daily. In a brainstorming session, participants accumulated ideas to deform daily-used objects.

The presented projects indicate a big interest in soft robotics and related shape-changing interfaces. However, design recommendations are scarce, in contrast designing soft robotics comprises challenges, that need further investigation to enable the development of novel applications and user experiences. Therefore, we aim to explore shape designs and application ideas in our research.

3 SHAPE DESIGNS

The potential for application fields for soft robotics has not been explored fully yet. Exploring possibilities of further application areas where soft robotics can be applied themselves comes along with the challenge of adaptable and useful designs of actuators. The shape design of actuators not only affects the appearance of the

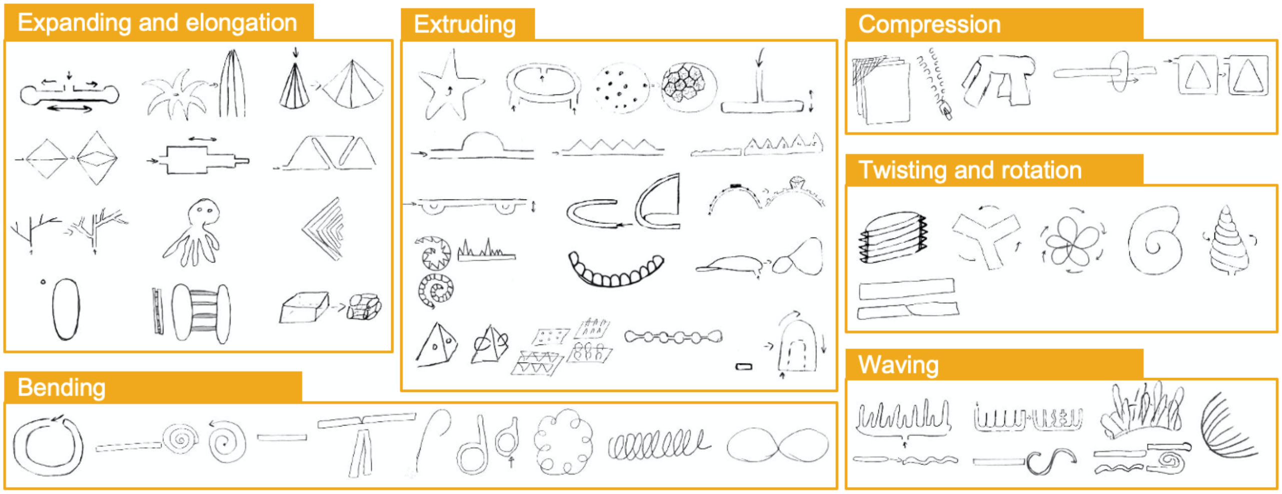

Figure 2: Excerpts from sketches, already categorised into six groups.

shape but also defines the possible movement when actuated. Hence, we created a pool of shape designs by conducting brainstorming sessions with users.

3.1 Brainstorming Sessions

We started by sketching actuator designs on our own, via pen and pencil. We ended up with 26 shape sketches. The majority of the sketches were inspired by the nature. After brainstorming on our own, we aimed to enrich the variety of shape designs and conducted a brainstorming session with four participants from different study and (or) work fields, including Human-Computer Interaction (HCI), Virtual Reality (VR) development, and Computational Biomedicine. Two participants had no previous knowledge of soft robotics. The session was conducted online via Zoom video conferencing, it took 1.5 hours, and participants were asked to sketch ideas.

We started the session by presenting soft robotic actuators to give participants an overview of the field. We are aware that this has an effect on the participants but it rather enhanced their sketches than biasing them. Before the brainstorming, we had informal discussions with users who had no experience with soft robotics and they were not able to draw any sketches without an introduction. Next, participants had 15 minutes to sketch their ideas. We had no specific criteria for the design except that the participants should estimate whether that movement is possible also as a physical object, e.g. as a soft robot actuated by air. The task was to sketch the shape design having a certain movement in mind. Participants brainstormed for the first 15 minutes without talking to each other beforehand to avoid generating bias. Afterward, participants shared their results with the others and explained their ideas. This discussion evoked new ideas from the participants for more different soft robots and their possible shape changes. To inspire even more ideas, we then presented sketches from our 26 shapes as examples of what the shape could look like. To give participants the opportunity to reconsider their ideas or to come up with new ones, another 15-minute brainstorming session followed. This session finished with participants' explanations of their shapes and associated movement ideas. In total, 30 new shape designs were sketched by participants and grouped by the different ways of movement: Extruding, Expanding and Elongation, Bending, Waving, Twisting and Rotation, and Compression. We chose to group the shapes by movement as we planned to show the participants the shapes executing a shape change in our user study. After the categorization, some of the shapes inside the categories were repetitive; therefore, a total 36 sketches of shape designs were derived in total (see Fig. 2).

3.2 Preparing Shape Movement

For investigating our research questions, it was crucial to provide a simulation of the shapes' movement during the user study. We used Autodesk Maya [1] and its animation mode for this purpose, since its support for complex movements and natural deformations make it a frequent choice in modeling and cartoon animation [12]. We recorded a video of every shape movement as a transformation from its start to its end shape and back, mimicking the process of filling and releasing air from a soft robot(see Fig. 3). We equalized the duration of this cycle to 10 s across shapes to make them comparable.

4 USER STUDY

The goal of our subsequent user study was to investigate what users associate with the movement of the shape designs (shape change) from our brainstorming sessions. We wanted to understand how users would interpret the shape designs and movement mechanisms, and what application areas they could imagine for each.

4.1 Study Design

After our brainstorming sessions, we ended up with 36 shapes, i.e., 36 conditions. Initially, we planned to conduct a within-subject study, but due to the number of experimental conditions and observations from a pilot study run, we decided that not every participant could test all conditions. However, a between-subjects design of

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[1] https://www.autodesk.com/products/maya

Figure 3: Start state (left), half actuation (middle) and full actuation (right) of our 36 shape designs.

course also comes with challenges, such as user bias. Therefore, we chose a compromise between a within-subject and between-subject design, and randomly assigned twelve out of the 36 shapes to each participant. To test every shape the same number of times, we ended up with 18 participants with a randomized sequence of twelve shapes each.

The independent variable in this study was the kind of shape motion: Extruding, Expanding and Elongation, Bending, Waving, Twisting and Rotation, and Compression. The dependent variables were: the association of the shape with any existing real object; the application field in which the shape can be used; the distinguishability of the shape movement; the comfort of interacting with the shape; its ability to interact with other objects; its ability to enhance interaction with users; and its trainability (ability to execute a different motion).

The experiment was conducted online via Zoom and using the visual collaboration platform Miro [2]. For every participant, we provided an interactive board with twelve frames. Each frame included a video of a 3D simulation of the shape movement, a questionnaire link, and space for sketching.

We recruited 18 participants (M = 26 y; SD = 2.29 y; 13 male, 5 female). 16 had a computer science background, one was from environmental sciences, and one was from sociology. All had used Zoom before; none had experience with soft robots or shape-changing interfaces.

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[2] http://www.miro.com

We started with a 5-minute introduction to soft robotics, with application examples in medicine, wearable devices, and fashion. Participants were invited to ask questions at any time during the experiment. Then, they logged into the Miro board, and we went through the questionnaire to ensure participants understood all questions, before we asked them to start with the first shape. The task for each shape was to first watch simulated shape movement video, then discuss two questions with the investigator:

- Does this shape remind you of anything? Do you have an association with an existing real-world object?
- Can you imagine a suitable application scenario for this soft actuator in everyday life?

Participants then filled out the questionnaire, and at the end were asked to sketch a modification of the shape design if they could think of one. The entire procedure took around 1.5 h per participant.

The data collected thus included participants' answers to qualitative questions about the associations with shapes and ideas for applications. The questionnaire consisted of five 5-point Likert scale questions, five yes-no questions, one multiple-choice question, and two open-ended questions for clarification.

4.2 Results

We collected qualitative and quantitative data in our user study. During the study procedure we realised that the quantitative data is not able to generate concrete results as the variety of applications in mind is very broad and different depending on the participant. In terms of completeness we still describe how we analysed this quantitative data.

The statistical analysis of the questionnaire consists of two parts: descriptive values and the Skillings-Mack test [3] for block design data. All descriptive results can be found in the supplementary.

Since there are more than two levels of the variable in each question (twelve), we initially thought about conducting a Friedman analysis. However, our data had missing values since each participant tested only one-third of all shapes. Therefore, a Friedman analysis could not be applied correctly. For that reason, we used the Skillings–Mack test, an adaptation of Friedman statistics for "missing data structure". It is based on the Monte Carlo method, so the result of the test depends on random resamplings [22]. Applying the test revealed that there is no significant difference between participants' answers except for Question 9 (*"Would you have liked to have more noticeable movement of the shape?"*) and Question 10 (*"Would you have increased the speed of the shape's motion?"*). Therefore, we focused our analysis on the user statements from our interview questions and the open-ended questions from the questionnaire.

The questionnaire had two open-ended questions. For Question 2 (*"Did your opinion related to the application scenario change after watching the whole movement simulation video (compared to the initial static view)?"*), participants mostly named a motion of the shape, not a specific application scenario. For 13 shapes, the video did not change the participant's ideas about the movement of the soft robot. The second was Question 5 *("Does this shape movement help provide certain predefined feedback to users?").* All shape designs can provide visual and tactile feedback when moving. However, we were interested in whether participants considered the feedback as a useful application for that shape. We found that our participants thought that most shapes could provide sensible feedback to the user, except shapes 3, 5, 13, 17, 23, 27, 30, and 33. Our participants also raised the idea of combining different feedback types that the shape could deliver, e. g., adding light or sound to the shape change.

Interviews were transcribed using the tool Otter [4]. For qualitative data analysis, we used MAXQDA [5]. First, we assigned codes manually to participants' statements. Next, we grouped codes into twelve main categories: Associations, Application, Shape modification, Movement modification, No functionality improvement, Shape design discussion, Movement design discussion, Uncertainty and problems, Comparison with other shapes within one experiment, Questionnaire clarification, Questionnaire answers discussion, and Side comments. Each of these main categories consisted of more precise subcategories. Finally, we executed a thematic analysis that identified the following themes inside each category:

- *Associations*
  - marine life, animals, and plants that produce an organic and natural way of movement (e.g shapes 9, 14, 15)
  - Everyday objects: food, well-known logos, symbols (e.g. shape 33), scissors (e.g. shape 2), wrist rest, plaster (e.g. shape 34)
  - Rigid objects: car details, screws, construction parts, furniture, and other rigid objects
  - Five shapes were clearly associated with one object by 14/18 participants who had tested the shape: Shape 1 - flower, shape 9 - shell, shape 15 - starfish, shape 23 - zipper, shape 36 - screw
- *Application*
  - medical devices, including massaging devices (shapes 13, 21, 25, 27, and 28), but also smart fabrics and jewelry (shapes 2, 4, 19, 29, 30, and 32)
  - No precise applications, but an action the shape can execute, such as, grasping, holding, and pushing objects, restricting the movement of other objects, crawling, and overcoming obstacles
- *Shape modification*
  - Circular shapes were preferred over other geometric figures (shapes 23, 33)
  - Participants stated to add more details about some of the shapes (e.g. for shapes 3, 11, and 14), but also simplify designs (e.g. for shapes 6, 16, 23, and 33)
  - Flattening of shape parts (e.g. for shapes 11, 12, and 36)
  - Modifications were done to improve the appearance of shapes, but not their functionality
- *Movement modification*
  - Expanding or elongation of the shape followed by shrinking movement
  - Bending or even wrapping of the shape around another object

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[3] Test in R: https://cran.r-project.org/web/packages/Skillings.Mack/Skillings.Mack.pdf

[4] https://otter.ai

[5] https://maxqda.com

5 DISCUSSION

Associations: As seen in the results, most associations were with marine life, possibly because the smooth movement reminded participants of swimming or floating in water. The other large category was everyday objects, likely because we try to connect new shapes to objects we already know well: *"It reminds me of a lipstick that's coming out"* [P2].

Applications: It seems that shapes with tube-like elements are most likely to be connected to medical applications: *"An endoscopic device that doctors use to put inside... when air is pushed in, it expands in some cavity"* [P3]. Rather than specific application actions, users often discussed what motion a shape can execute, such as grasping, holding, or interacting with other objects. This lets us assume that a soft robot is mostly characterized by its movement ability. This motion determines in what fields the soft robot can be applied.

Distinguishability, Comfort, Interactivity & Trainability: We observed that users tended to prefer simple shapes, i.e., with not too many details, and rounded shapes (*"It doesn't have to be that pointy; it could be rounder"*, P14). Furthermore, e.g., P5 suggested that objects that are mostly rigid could be transformed into soft robots and still have the same function (*"This kind of twisted shape reminds me of a drill and drilling parts"*). This is an interesting approach, as the object could adopt the advantages of soft robotics, such as flexibility, although one needs to verify what rigid characteristics can be omitted. For 32 shapes, the movement was clear. For the remaining four (Shape 3, Shape 12, Shape 21, Shape 33), participants were not sure about the movement.

Considerations for Shape Design. The considerations result from our first exploration of soft robotic shape designs.

Daily Devices: Transform a device made for one use case into one for more use cases. Especially during the interviews, we felt that participants often tried to imagine soft robots for tasks that are usually done with rigid objects. We believe one argument for them is that if the object can change its shape, the same device might be useful for more than one application, e.g., a screwdriver may change from crosshead to slotted.

Abstract Design: Soft robots do not need a lot of details, but clear affordances. Participants tended to redesign shapes with small details into more abstract objects. The level of abstraction is important as the purpose of the details should not be lost. For example, a door handle can indicate whether a person may enter the room or not by little spikes showing up on the handle or not. The amount of those spikes is also enough as soon as it is clear that they are visible, i.e. around 10 spikes are enough, and e.g. a design with 100 spikes would be too detailed.

Motion Design: Design clear signifiers of what motion the soft robot can execute. It seems participants could imagine a suitable motion for a soft robot quite well. Even though we asked for applications, they mainly discussed the movement direction or deformation of each shape. This lets us assume that users might be able to reuse soft robots for various applications that utilize the same motion., e.g. arrows depicting what part of a soft robot may move in the direction of the arrow, or a small icon of the final shape change appearance. All these indicators should help the user to decide whether the possible shape change or movement of the soft robot is helpful for their use case.

6 LIMITATIONS & FUTURE WORK

This user study showed animated 3D objects to participants, because of the pandemic and since fabricating these shapes is non-trivial [5]. We believe it is worth investigating the same questions with real physical objects though. We plan to prototype some shape-changing soft robots to validate and enhance the results. As fabricating some shapes might be quite challenging, it is important to choose the shapes from our design pool carefully. The most interesting shapes from this study could be fabricated and re-tested as physical objects.

Our participants mentioned that, in this online setup, it was hard to know how big the shapes would be in reality (*"How big are those shapes? They could be on the microscopic range, the meter-high range... it is purely abstract"*, P11). Using physical objects would address this issue.

Our user study was set up very explorative, serving as a starting point to inestigate shape designs and shape changes of soft robots. We are aware that future research needs to dig deeper into the single association types that we found, also studying even more design ideas. We have developed a starting pool of soft robotic shapes with our brainstorming sessions. Still, we showed preselected designs to our participants in the user study which may limit the findings. We hope to start more discussions on shape designs and shape changes for soft robotic applications with this work, leading also to bigger design pools that can be tested with users.

Smart textiles and fashion were frequently mentioned as application areas. In particular, participants suggested augmenting the soft actuators with light or sound options, to provide extra visual and auditory feedback. Such features could be embedded into our shape designs for additional studies.

7 CONCLUSION

We presented an explorative investigation of shape designs for soft robotics. Soft robots offer flexibility and adaptability, making them useful in various application areas, from medicine to industry and fashion. However, their potential has not been fully explored yet. We wanted to understand how users interpret new shape designs and their movement mechanisms, and how they would apply them. Hence, we developed 36 shapes in brainstorming sessions with users and tested them in a subsequent user study. From our findings, we derived first design recommendations for soft robotics shapes. In the future, we aim to further study the effects of these shape designs, but with physical objects. We also intend to further explore the emotional effects soft robot movement may have on users.

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