A Basic Form Language for Shape-Changing Interfaces

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ABSTRACT
In this paper we propose a basic form language for shape-changing forms that work independently of materials and contexts of use. This form language is meant to inform design practice and therefore it is essential that it is easily graspable and available. Instead of relying on post analyses and abstract concepts, the basic form language we propose has the potential to become a vernacular that is relevant for practitioners. We derive at the language through looking towards adjacent fields of architecture and industrial design as well as through our own practice. We qualify the relevancy of the language in three ways: through using it in practice both as generative for our designs, as means to communicate with external collaborators, and finally we demonstrate its analytical power through analyzing three shape-changing interfaces made by others.

Author Keywords
Shape-changing interfaces, formgiving, form language, point, line, plane, volume, force, design practice

ACM Classification Keywords
H.5.m. Information interfaces and presentation

INTRODUCTION
Artifacts and surfaces that can change their physical shape are receiving increasing attention in art, design, and architecture [cf. 6; 9; 2; 16]. Within HCI, interaction design, and particularly tangible interaction, shape-changes have been explored to develop new forms of information displays [cf. 12; 7; 14; 15; 10].

Introducing an extra physical dimension in the form design of human computer interaction poses some challenges for the designer. Basically, we need to learn how users in various contexts interpret shape-changes [cf. 15; 10] but before we get into this we need to understand and become able to articulate the new expressive design space that shape-change enables [cf. 1]. Current attempts to develop a language to describe shape-changes have provided a set of form descriptors based on analyzing a series of examples [7; 14]. These languages or series of concepts (e.g. [14] proposes: orientation, form, volume, texture, viscosity, spatiality, permeability, adding/subtracting, qualities, personality traits, organic, mechanical) are, as the authors note themselves, not mutually exclusive, which poses challenges of clarity when used in a design practice [11]. Further, the ontologies they represent have a tendency to cultural specificity and arbitrariness not unlike natural philosopher John Wilkins categories for his universal language [cf. 3]. This tendency is likely the result of the proposed languages being based on artifact analyses rather than being developed within a design practice [cf. 21].

In this paper we propose the primary elements in a form language for shape-changing interfaces that works independently of materials and contexts of use. We propose these general form elements to help inform basic form literacy in interaction design as a formgiving practice [18]. Adjacent fields such as architecture and industrial design have similar form traditions and we derive at the proposed form language by appropriating form elements from architecture to encompass elements relevant for shape-change. The aim is to offer a vernacular for design practitioners, which is why the form language must be easily graspable and available.

We qualify the relevancy of the language in three ways: Through using it in practice as generative for our designs (see Figure 1), as means to communicate with external collaborators, and finally, we demonstrate its analytical power through analyzing three shape-changing interfaces made by others. This basic form language can be developed further as the field matures and is, for instance, easily expanded to include notions of temporal form when they are discerned [cf. 19].

Figure 1. Two shape-changing interfaces generated from the basic form language. Left: Tiling/Plate
Right: Bending/Arches
FORM LANGUAGE
A form language for shape-changing interfaces must include both the primary form elements, their compositional principles as well as guiding rules for form compositions. Such a form language will assist designers in defining form matters of the design gestalt and its compositional expressions by providing a vocabulary for aspects of the design process that can sometimes be difficult or even tacit to articulate. Furthermore, a form language is also a way to push forward the importance for attending to these matters in interaction design. The form language must be a manifestation of a form tradition for shape-changing interfaces, in that, it must frame the ways in which we can discuss shape-change. As the architecture writer Francis Ching writes:

“Designers inevitably and instinctively prefigure solutions to the problems they are confronted with, but the depth and range of their design vocabulary influence both their perception of a question and the shaping of its answer. If one’s understanding of a form language is limited, then the range of possible solutions to a problem will also be limited” [5, p. IX].

In this sense, the scope of the form language is to offer a new Wittgensteinian language-game for HCI and interaction design [21]. A language-game is the rules for our communication in our practice; or as Pelle Ehn writes:

“To follow the rules in practice means to be able to act in a way that others in the game can understand. These rules are ‘embedded’ in a given practice from which they cannot be distinguished. They are this practice. To know them is to ‘embody’ them, to be able to practically apply them to a principally open class of cases” [8, p. 106].

The form language, as a language-game, is therefore important for both bringing attention to form and expression in design practice as well as for sharing and communicating with others. Since the language-game is grounded in use, the way to develop and expand a form language for shape-changing interfaces is through design practice. This continuous development can eventually lead to an elaborate and comprehensive form tradition, as known in adjacent fields such as architecture and industrial design [18].

In architecture, for example, form can be described by the use of four primary elements: Point, line, plane, and volume [cf. 5]. These elements are the basic vocabulary that the architects use to develop more elaborate forms. While the form language of architecture is more complex than those four elements, the identification and study of this basic vocabulary enable the architects to qualify their design practice and broaden their ability to imagine new design possibilities. Ching [5] even argues that the study of form should be one of the initial focal points for any new architect. He argues that similarly to the need for understanding the alphabet as a prerequisite for making words and writing novels, the architect’s ability to recognize the primary elements is a prerequisite for the understanding of how these can be manipulated and organized and eventually be used to address the more vital issues of meaning in architecture [5, p. IX].

Likewise, a form approach to shape-changing interfaces is about identifying the primary elements of shape-change in order to understand the various potentials. From here, it will be clear how to proceed to explore and articulate their potential in HCI and interaction design. However, a form language is not in itself what will develop form literacy about shape-changing interfaces, rather, it is the way the form language is given meaning through practical use: “One cannot guess how a word functions. One has to look at its use and learn from that” [21, para.340]. As such, we must begin to use the form language to expand its meaning for the language-game of shape-changing expressions in order to inform interaction design practice. First, however, we need to consider the basic concepts relevant for such a form language. In order to identify the primary elements of shape-changing interfaces within HCI and interaction design we must understand the design practice surrounding them – that is, the practice of formgiving.

GIVING FORM TO SHAPE-CHANGE
When a glassblower shapes a vase or a silversmith gives form to a new chalice, they work with a single material in which they reveal an object’s final form. When architects give form to a new house, however, they do not work directly with the bricks or other materials that will make up the house. Instead, architects make drawings or scale models as a way to reveal the overall form compositions of a new building. This enables them to alternate between delving into details or zoom out on the landscape [cf. 5]. As a result of these processes a final form for a house – or another kind of design – emerges. This final form can then be prepared and interpreted into building instructions for actual construction. Indeed, formgiving for the architect deals with the complex expressional unity rather than specific details on construction.

While Vallgårda and Sokoler [20] have previously compared formgiving in interaction design to the practice of glassblowing this may not embrace all the complexities of giving form to computational things. Indeed, Vallgårda [18] later identifies three form-elements of interaction design: the physical form, the temporal form, and the interaction gestalt. Where the physical form denotes the material shape of the thing, the temporal form denotes the changes of expressions over time caused by the computer program and interactions, and finally, the interaction gestalt denotes the complete picture of actions with and around the thing [18]. Interaction designers cannot give form to the entire thing in one confined process, but must work with different elements in different stages of the process. The three form elements are equally present when designing shape-changing interfaces. While the physical form in HCI and
interaction design is often pre-defined as a smartphone or a laptop; this is particularly not the case within tangible computing and shape-changing interfaces. Here, interaction designers have to consider both the three form components individually as well as their compositional relationship. Indeed, the physical form must be developed; not in isolation, but with the temporal form and interaction gestalt in mind. Also, the technological set-up and the appropriate temporal form must be configured to match the other form components. As such, formgiving of shape-changing interfaces is highly complex, and bears resemblance to the architectural practice of exploring both the overall as well as subparts of the overall design gestalt.

Moreover, formgiving processes in interaction design will go through different stages. Given that the design of shape-changing interfaces is still in its infancy, the initial formgiving may be characterized as more exploratory investigations, whereas later stages of the process closer to an actual prototype or product will include more normative and defining decisions [cf. 4]. As such, the formgiving process does not always only appear as a process of revealing and releasing material potentials, but can shift between different modes and purposes.

The physical form of a shape-changing thing is, like any other thing, the physical configuration of both its three-dimensional shape, the materials from which it is made, its color as well as other characteristics that define its appearance. The form is the way a thing exists in the world; it is, the holistic composition of its entire gestalt. However, shape-changing things are different from many other things due to their ability to dynamically change their shape. As such, their forms are not static, but changes as a result of their inherent computational capacities.

**BASIC FORM LANGUAGE FOR SHAPE-CHANGING INTERFACES**

As argued above, the interaction designer’s practice is closer to that of architecture than to that of craft. Thus, looking to the seasoned practice of architecture and its primary form elements seems like a meaningful place to start.

As also stated above, form in architecture can be described by the use of four primary elements: point, line, plane, and volume [cf. 5]. The point is a position in space that has no direction, spatial dimensions or dynamics. A point can serve to mark different intersections between elements, the center or the end of an object. The expansion of one point to two points produces a line, which has a beginning and an end, which gives it a length as well as a direction. A line can be used to describe a conceptual line within an object or to articulate the edges of a shape. Two non-parallel lines form a plane. Planes can be used to describe the two-dimensional shape of an object. Besides length, the plane therefore also has width. This gives it a spatial expanse, which allows it to hold properties of color, texture, or patterns. A plane extended becomes a volume, which has width, length, and height. It has a three-dimensional extent and is what encases an object’s form.

Since the physical form in its abstraction is the same in architecture and interaction design these four basic elements should be directly transferable to an interaction design practice.

Further, the four form elements are not sufficient when it comes to describing the entire gestalt of shape-changing interfaces, as these also comprise temporal dynamics. Therefore, the form language of shape-changing interfaces must encompass other elements to sufficiently describe these aspects. By definition, the temporal form in shape-changing interfaces comes to expression as spatial changes in the physical form. The interest here is how the temporal form translates into physical changes in the shape-changing interfaces; that is, how it enters into compositional relationships with the rest of the thing’s gestalt. Consequently, we propose that a form language for shape-changing interfaces deals not only with the physical and the temporal form separately, but also focuses on a common vocabulary for the way in which the temporal dynamics are expressed in the physical form.

We propose ‘force’ as a fifth element to encompass the temporal dynamics within the physical form. The primary elements in a form language for shape-changing interfaces will thus be: point, line, plane, volume, and force (see Figure 2).

Both Togler et al. [17] and Coelho and Zigelbaum [7] have already used the concept of force to describe how a temporal structure can alter the physical form of an interface or material. Coelho and Zigelbaum [7] as a concept to denote the amount of force embedded in the materials in respect to the surrounding forces of gravity etc. where Togler et al. [17] use it more simply to describe the nature of the shape-changes in their Thrift Faucet. In physics, a force can cause changes to an object. It is denoted as a vector, which gives it an entry point on the

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**Figure 2.** The five primary elements of shape-changing interfaces: point, line, plane, volume, and force.
describe multiple forces applied to an object. Therefore, forces contain information about both where on the object changes occur, the magnitude of the changes in the object, as well as the orientation of these changes; all attributes that are also relevant for describing interactive things. However, while a physicist would describe multiple forces applied to an object (e.g. gravity, friction, and applied forces) we find a more perceptually driven use of force is more easily adopted in design practice. Thus, we advocate for focusing on the resultant force (that is, the sum of all force vectors on an object [cf. 22]), or maybe more intuitively, the perceived force. Essentially, this concept of force helps us to denote the transformations that occur within the shape of the thing. It becomes the link between the physical form and the temporal form of the changes in the shape.

This is a theoretical proposal of five form elements to constitute a basic form language for shape-changing interfaces and as argued above they only gain their meaning through use in practice. In the remainder of this paper we will use this basic language in three different contexts of practice: as generative for the design of shape-changing interfaces, as communicative with third party regarding the construction of shape-changing interfaces, and as analytical to explain the forms of three shape-changing interfaces.

GENERATIVE FOR DESIGN
In our design process, the notions of the point, the line, the plane, the volume, and the force were, on one hand, the consistent theme that served as an inspirational framing, but on the other hand they were themselves informed through the experiments. For instance, we would begin exploring how the plane could serve as a generative concept for interesting shape-changes, and in turn the resultant composition would inform the plane as a form element.

With the planar form element as a starting point we began exploring how different forces applied. Here the notion of the point helped explore different constructions and aesthetics simultaneously. Through a series of simple mock-ups in various materials (textile, plastic, and wood) we explored what a plane was and the many different ways it could change shape (see Figure 3).

We later chose to continue with two shape-changing prototypes, which could be realized through a construction of steel and with two motors. We chose steel because it exhibits material properties that allow for both a rigid and a bendable plane. We chose two motors as two allow for more complex expressions than one while still keeping the experiments relatively simple.

Tilting|Plate
In this first prototype we started out with a simple rigid steel plane (see Figure 4). In order to achieve a shape-changing form we nested it within two other hollow planes. The rigid plane is attached at exactly two points in the inner of the hollow plane and the frame defining this hollow plane is attached at exactly two points to the outermost hollow plane. When all planes are in level they form a closed box. Since the inner rigid plane can rotate around one axis and is attached to the second plane, which in turn can rotate around the perpendicular axis, the inner rigid plane appears to be able to move in all directions. The servomotors within the box each apply force on an axis enabling control of the changes.

We had in our earlier explorations experimented with the size of the frames of the two hollow planes in respect to the rigid plane to explore what consequences that would have for the overall expression. We realized that keeping the frames of the outer hollow planes narrow increased the attention on the inner rigid plane, resulting in a stronger overall experience of a floating plane. Indeed, the Tilting|Plate exhibits a dynamic expression where the rigid plane appears almost to be floating, due to the fact that its movements appear to be entirely independent from the rest of the box.

Further, it proved crucial for the sense of a floating plane that the force was applied in points forming a line of symmetry in the middle of the each movable planes and that the two lines were orthogonal to each other.

The amount of force applied would influence the resulting volume the tilted planes would create above the steel box. Here, we realized that the more perpendicular the rigid plane came to its origin the illusion of the floating plane was scattered and the three planes were perceived independently.
Bending Arches

In the second experiment we started out with a bendable plane. By cutting it up into series of bendable rectangular steel planes suspended into arches we were able to gain an overall more complex expression of shape-change (see Figure 5). Within the volume defined by the arches run a linear crossbar. Each arch is attached in exactly one point to the crossbar by a string and the position of this point on the arch determines how it is bending. The crossbar has the potential of a downward pulling force in each end, which can be activated or relaxed independently. These changes result in a dynamic change of volume under the arches.

We experimented with different positions of the attachment on the arches. By placing them in a line running through the arches we would achieve a symmetrical expression of the shape-changes but by placing them in a non-linear fashion we achieved a much more complex expression of shape-change.

Further, we experimented with the width of the arches and we aimed for an overall expression of one plane that could scatter into a myriad of narrow planes. We discovered, in line with general gestalt principles, that the wider the individual planes were the more they became planes in their own right and less part of a whole. The narrower they became the less they appeared like planes and more like lines. Thus we opted for a middle way with ten narrow planes of equal size.

Generally, we discovered how the flexibility of the language enabled us to explore the many different expressions of a plane while never needing to look for new form elements to describe what we were working with. Indeed, the planar element could be used for multiple things: as a rigid plane, a hollow plane only defined by a frame, a bendable plane made up of a series of narrow planes, etc. The vocabulary was generative to our design. The concepts enabled us to discuss and identify elements across the prototypes, but at the same time the draw attention to similar aspects of them. Just as importantly is, however, that it was easy to use. We did not have to learn it as it was readily vernacular, although, we were probably more conscious of using it given the purpose of the experiments.

COMMUNICATION WITH THIRD PARTY

We engaged a steel division in an offshore, marine, and energy company to produce the two prototypes. In other words, a company used to manufacture steel structures but not at all used to working with non-engineers and non-technical drawings. As primary means of communication we used schematic drawings of the two prototypes made using the basic form language and including rough measurements (see Figure 6).

Based on these drawings and a video of the plastic mock-ups we were able to discuss the quality of the steel to be used. Generally, the language allowed us to discuss both details as well as the overall construction with the company. For example, the positions of the connecting bolts in Tilting Plate were decisive for its symmetric movements and therefore for the overall expression. Illustrating the bolts with points on the planes enabled us communicate their positions unambiguously. Another example was how we discussed the scale and volume of the boxes. Together we were able to determine the necessary height of the box. It had to be large enough to encompass a desired maximum oscillation of the embedded planes. A third example was how we were able to determine the appropriate type of steel for the arches in Bending Arches by together finding the lowest possible levels of necessary force to bend the arches.
The form language was therefore not only important to describe and communicate the form composition of the construction, but also to illustrate the expressional and aesthetic goals of the prototypes. Due to the simple nature of the form language it did not require any prerequisites. It was readily available for everyone involved and we could easily use and refer to the primary form elements our discussions.

FORM ANALYSES OF SHAPE-CHANGING INTERFACES
To further develop the form language and to challenge it beyond our own work we use it to analyze three examples of shape-changing interfaces. The purpose is to use the basic form language to understand the compositional structures as well as dynamics of the shape-changing interfaces.

Topobo: Points on a line and rotating volumes
The interactive toy, Topobo, consists of modular pieces that can be connected to create animal-like robots: “By snapping together a combination of static and motorized components, people can quickly assemble dynamic biomorphic forms like animals and skeletons” [13, p. 64]. Figure 7 shows an image of Topobo as well as a schematic drawing of how the object can be regarded as a composition of the basic form elements.

The static components are denoted as points that are attached on a line. While the static components are not simply points in the physical object, it is a way to use the design vocabulary to make meaning of the form dynamics of Topobo. In order to understand the mechanism and dynamics in Topobo, it is less relevant which specific shape the static components have. The interesting aspect is instead the relation between these elements. Thus, the form language appears to scale. We recognize this from how it is used within architecture, where the point is sometimes used to denote a specific nail in a construction, but at other times is used to position monuments on city scale [5].

Collectively, the points on lines make up volumes, which we have separated depending on their internal relationships. The “neck/head” of the object is one volume whereas the “tail” is another. By defining the static elements as a volume it is possible to describe the collection of these as a whole, which makes it simpler to understand the dynamics of the object. Each of these volumes is attached to a motorized component (the light grey spherical volumes), which applies a rotational force to the neck/head, tail and to the four legs respectively. This way, Topobo is able to turn its parts, and depending on the way it has been assembled it moves accordingly.

While the form language could have been used to describe the object in more detail (for instance, the specific form of the static elements or the different ways they could be attached), we have here used the vocabulary as a way to understand the overall form composition and logic as well as using the concept of volume to articulate the moving parts of Topobo.

Morphees: A bending plane with a planar force
Roudaut et al. [15] understand their Morphees interfaces as meshes of physical points that can be controlled to make them change shape. Instead of a mesh, we propose to see Morphees as a flexible and bendable plane (see Figure 8).

Overall, a Morphee can be seen as planar element that is affected by forces, which in different ways creates its curling movements. However, where the forces in Topobo and our own prototypes came from specific points the force or forces in the Morphees are sometimes distributed in the entire plane. In one, the forces are distributed into the entire plane (see top drawing in Figure 8) and in the other; the
The distinction in descriptions allows us to understand control over the shape forces, each represent a force vector. Their applications on the plane is divided into subplanes which can be bend following multiple lines [15].

The distinction in descriptions allows us to understand the distinctions in what we can use them for in terms of shape-changing interfaces. Indeed, we are able to use the form language to make explicit how the Morphees’ expressions differ.

**Thrifty Faucet: Composition of lines, points, and forces**

The shape-changing faucet by Togler et al. [17] can be regarded as either one line with multiple points or as a collection of lines joined in succession by points (see Figure 9 right top and bottom respectively). Each point has the potential of a multidirectional force which, when activated, will change the shape of the line or the relationship between multiple lines depending on the perspective. As the shape is altered, the overall volume of the faucet changes accordingly. Which description to choose depends on what makes sense for the context at hand. One emphasizes the coherency of the faucet as one object with multiple points of forces the other emphasizes how the different parts can move individually.

The Faucet can curl in a coherent movement throughout all lines (or points in the line) or it can move some lines in one direction, while the rest moves in another direction. Since the parts of the faucet can move in multiple directions at the same time, it is not sufficient to describe the movements with only one force. Instead, multiple forces must be used to encompass this more complicated movement patterns. In Figure 9 we show how forces in different directions applied to two consecutive points can make the tip of the faucet move in one direction, while the rest of it moves in the opposite direction.

With analyses of these three prototypes we have seen that the basic form language, as a lens, has indeed made it possible to discuss the objects’ actuated form dynamics. This is highly relevant for designing the interaction for them; just as we know how pixels behave on a screen we need to know how the shape-changes occur and where we can affect them. Indeed, for each new design of a shape-changing interface we need to know its actuated form dynamics in order to get to the next step of interaction. Moreover, we have seen how the language offers flexibility in the sense that it can be used on various levels, which allows it to describe the appropriate and meaningful details for the task at hand.

**DISCUSSION**

With the primary form elements: point, line, plane, volume, and force we propose a basic form language to articulate the design space of shape-changing interfaces. We have used the language as generative, as communicative and as analytic showing its robustness in articulating the dynamics of the form changes in shape-changing interfaces. We further believe this language can be used to describe even more complex compositions and that it is a generative platform for developing these complex gestalts.

As we argued in the beginning, a useful form language must enable us to describe the dynamic forms of shape-changing interfaces and do so in a manner that takes the expectations and conventions for shape-changing interfaces into account. Shape-changing interfaces are characterized by physical actuations and a useful language must therefore encompass these dynamics. This is what the concept of force does in correlation with the other four. The proposed form language is not arbitrarily defined but grounded in a combination of the adjacent architectural practice and our own much younger interaction design practice. Further, it includes the primary form elements, the compositional principles, and guiding rules for form compositions as we have shown in practice, especially through the analysis of existing prototypes. Indeed, this form language has the potential to become the formalization of the form tradition of shape-changing interfaces and as such a manifestation of the language-game as it provides a useful frame for how we can discuss shape-change.
This is still a basic form language and the way to develop and expand it is to use it. This paper has proposed the initial steps towards a better form literacy about shape-changing interfaces. We have presented the five primary form elements, which must be explored, challenged and developed in order to take the form language further towards a more coherent and sufficient form tradition that can embrace the complexity of compositional rules and guiding principles for designing with shape-change.

With our design practice, we have begun to give meaning to the the primary elements and come to realize some of its strengths and limitations. Primarily, we have demonstrated its relevance and robustness. Through our three types of applications we show its relevance, as we are able to precisely articulate the critical aspects of shape-changing interfaces that enables us to discuss possible ways of interacting with them. Just as we know and precisely can articulate how pixels behave on a screen we can now also understand and articulate the design space of shape-changing interfaces. Further, we have shown its robustness as a flexible tool for understanding form dimensions. We have demonstrated how it can be used as a flexible lens for the task at hand, which can provide designers with different descriptions each highlighting aspects potentially useful for designing the interactions with them. Indeed, the primarily form elements can be used for descriptions both at a grand scale and in close-up without loosing their meaning.

Further, the specific contribution to the classic architectural form language is the concept of the force. ‘Force’ is what enables us to go from static forms into the dynamic realm of shape-change. It is what will enable us to articulate how the physical and the temporal form intertwine. Future work will then entail to develop the language that enables us to articulate all the primary elements of the temporal form eventually allowing interaction design to become fully-fledged formgiving practice.

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