Lorenzo Guiducci and Heidi Jalkh

On Material Grammar: Learning from and Designing with Unstable Behavior in Thin Sheet Materials

Abstract

Structural instabilities in thin materials can both cause failure (e. g., when compressing a soda can) and give rise to beautiful morphogenetic phenomena (e. g., undulations in leaves edges). Here, we present our recent work on the design, mechanics, and performativity of a designed thin sheet undergoing such structural instabilities. We laser cut an inverted honeycomb from a thin sheet of polymeric foam, thereby bestowing it with auxetic properties. This design is then modified in order to introduce a self-locking mechanism, allowing the hexagonal cells to lock in an expanded, open state. The result is a sort of "augmented surface" that can be operated by simple pulling actions on its edges, activated and reset, programmed and reprogrammed. In this process, we realize that this surface has a material grammar, describing how single cells (as letters/symbols) are put together into periodic structures (as sentences) that can transform or create complex behavior (as meaning). For the reader, we hope this article illustrates some of the virtues of such transdisciplinary investigations, and how the resulting physical outcomes are indeed boundary objects, prefiguring a fertile space for research questions and opportunities in the fields of engineering, architecture, design, and performative arts.

Structural Instabilities in Thin Sheet Materials

In engineering, instabilities have been a matter of avoidance and prevention for a long time. Modeling how a technical system works, developing a suitable design, predicting possible sources of misbehavior or failure, these were—and still are—an engineer's primary goals, with instabilities and nonlinearities prefiguring the most concerns. At the same time, quite the opposite perspective can be derived from the biological sciences, where instabilities are usually at the origin of many—and beautiful—morphogenetic processes (such as the unfolding of petals and flowers upon blooming). In the last few decades, this positive connotation toward instabilities has been embraced by engineering sciences, originating the new field of mechanical metamaterials: elastic materials with a controlled geometry undergoing reversible structural instabilities, providing material scientists with a novel, geometric route toward material properties

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design.[1] One of these "augmenting" properties, particularly relevant for this contribution, is *auxeticity.*[2]

Researchers have been investigating auxetic surfaces by endowing sheets with an ordered pattern of cuts (as in the ancient Japanese art of *kirigami*) for some years.[3] Some of these examples show programmable textures where the cuts imprint a visual pattern on a sheet of material that is being stretched.[4] The pattern is invisible in the original relaxed state of the sheet and appears when the sheet is stretched; it therefore works as a physical data support in which information is read through a pulling action. Auxetic surface applications extend the domain of material science and can also be found in the disciplines of design, art, and architecture, where they are used as physical, responsive interfaces between humans and the built environment, for their unusual and unexpected mechanical behavior.[5] Other notable examples have shown innovative ways to leverage auxetic surface properties to design and fabricate self-supported, free-form surfaces.[6] Chen et al. proposed a specific cut pattern that not only endows a sheet with auxetic behavior, but also makes it bistable: thus, the sheet can switch between a closed, contracted state and an open, expanded one, with the possibility to program a structurally stable, target 3D surface.

In the spirit of these research works, our aim was to explore the deformation behavior of thin sheets bestowed with a pattern of cuts. We were fascinated by the possibility to create physical surfaces with unexpected morphing behavior using the "tools" of geometry and structural instabilities, to formulate new research questions about how this works, or possible uses. The exploration of the design space had to be primarily performed through simple, table-top experiments, allowing us to combine our different skill sets (from design and engineering) in a curiosity driven, transdisciplinary research experience.

1 Dennis M. Kochmann and Katia Bertoldi, "Exploiting Microstructural Instabilities in Solids and Structures: From Metamaterials to Structural Transitions," *Applied Mechanics Reviews* 69, no. 5 (2017), https://doi.org/10.1115/1.4037966.

2 A material is called auxetic if, upon stretching, it expands transversally to the stretch direction.

3 Ahmad Rafsanjani and Katia Bertoldi, "Buckling-Induced Kirigami," *Physical Review Letters* 118, no. 8 (2017), https://doi.org/10.1103/PhysRevLett.118.084301.

4 Ning An et al., "Programmable Hierarchical Kirigami," *Advanced Functional Materials* 30, no. 6 (2020), https://doi.org/10.1002/adfm.201906711.

5 Nassia Iglessis, "Urban Imprint," (2019), accessed March 15, 2022. https://www.nassia-inglessis.com/works-recent#/urban-imprint-1/.

6 Tian Chen et al., "Bistable auxetic surface structures," *ACM Transactions on Graphics (TOG)* 40, no. 4 (2021): 1–9, https://doi.org/10.1145/3450626.3459940.

Auxetic Surfaces Based on the Inverted Hexagonal Cell

As the design space of possible auxetic structures is practically boundless, we focused on the well-studied reentrant honeycomb design (in which two opposite internal angles of the base hexagonal cell are larger than 180 degrees) for which an intuitive understanding of the deformation behavior was possible. In addition, digital fabrication methods and craft-making have been used as an experimental research activity of making and thinking. The models for this work were manufactured with laser cutting, using three-millimeter-thick foam (EVA rubber) as the base material, allowing many tests to be carried out in short periods of time. Such a mix of methods, facile prototyping, and different disciplinary backgrounds allowed us to quickly test hypotheses and explore the available design space for cellular structures comprising inverted hexagonal cells.

A useful consequence of auxeticity is the larger shear to bulk modulus ratio: auxetic materials can be more easily stretched or compressed (large direct deformations) than distorted (small shear deformations). In an inverted hexagon, this can be traced back to the kinematics of a geometrically identical six-sided closed linkage. Compared with convex hexagons, inverted hexagons can achieve larger deformations upon stretching along their short axis: much like in the closed linkage, the reentrant sides of the hexagon rotate outward until a convex hexagonal shape is reached (fig. 1). By assembling convex polygons and inverted hexagons into a single cellular structure, the large extension of the inverted hexagon is frustrated by an adjacent convex polygon. In a thick honeycomb material, this incompatibility would cause a localized deformation in the cell walls; but since our prototypes are cut out of a thin sheet, the cell walls buckle, participating into a global out-of-plane deformation. Thus, in a simple structure consisting of four convex cells and four inverted hexagons, a simple pulling action already generates a large flat-to-spatial transition that was used to create a gripping mechanism (fig. 2).[7]

Exploration of 3D Morphing and "Locked" Cell Design

While the out-of-plane deformation resulted from differences in local expansion (i. e., at the cell level), the actual flat-to-spatial morphing also depended on the size of the system (i. e., number of cells in the structure). Therefore, we kept exploring several possible geometric designs, looking for new and unexpected behavior emerging from different combinations of the same cells. Importantly, we worked in a hands-on manner,

7 Heidi Jalkh, *Making Matter Active through Form: Fabricating Bio-inspired Behavior with Auxetic Structures*, master's thesis (Humboldt-Universität zu Berlin, 2020).

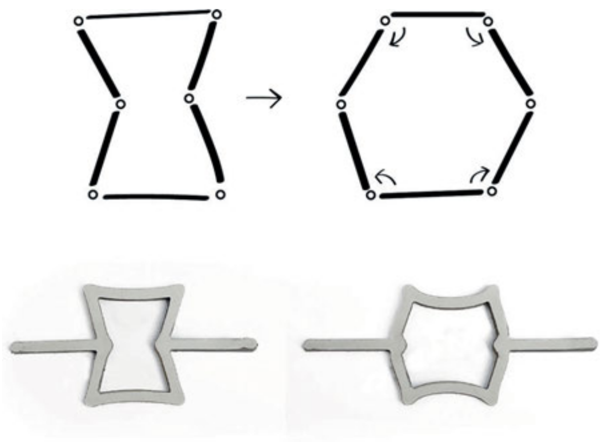

Fig. 1: When an inverted hexagon is stretched, the sides bend to reach a convex shape. The overall shape change is similar to the kinematics of a rigid six-sided closed linkage with floppy joints.

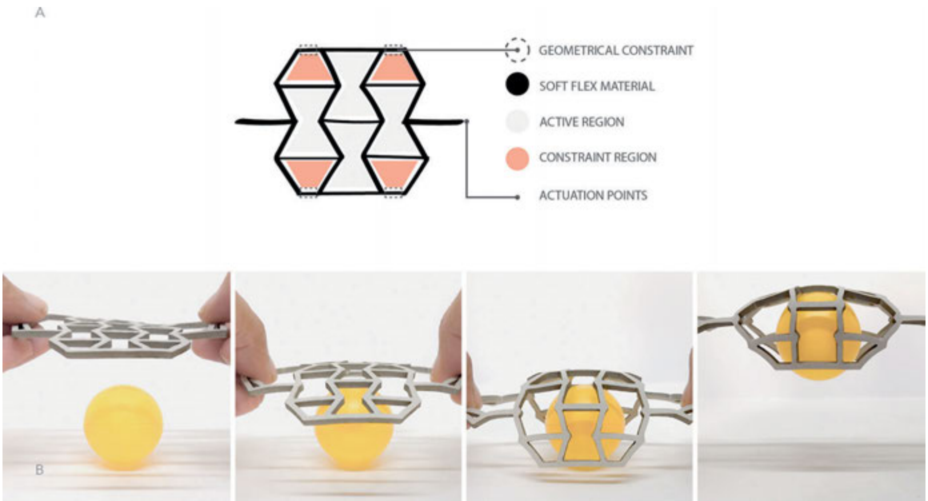

Fig. 2: (2A) 2D geometry and parameters for the design of an active structure that morphs out of the plane upon stretching; (2B) Gripping demonstration of an auxetic soft gripper picking up a 32 mm ping-pong ball.

proposing designs with a certain expected behavior, verifying our hypotheses and assumptions, and then modifying them according to our observations. By comparing, discarding, isolating, and modifying, we developed a certain intuition about what was possible to achieve in terms of spatial morphing, but also realized potentially interesting qualities of these auxetic surfaces, and bumped into some of their limitations. For example, the cellular structures worked as simple springs, that is, they could transform the elastic work from the pulling action (stimulus) into a more complex spatial reconfiguration, but this elastic energy could not be stored after the stimulus ended. While fixing the structure on its outer contour could be a solution (see fig. 3), we aimed at locking the deformation in the structure itself, thus creating a material/surface that would function as an integrated spring and latch system.

To achieve this, we reconsidered the hexagonal cell kinematics upon stretching (fig. 1), and particularly how the inclined beams almost perfectly rotate around their endpoints: thus, we reasoned, by adding appendages on two opposite inclined beams (represented by the pins piercing through the beams in fig. 3), we could create a state of self-contact in the cell while preserving its symmetries. Finally, we shaped the appendages in the form of darts such that they could be set in mechanical engagement, locking the cell in its open state.

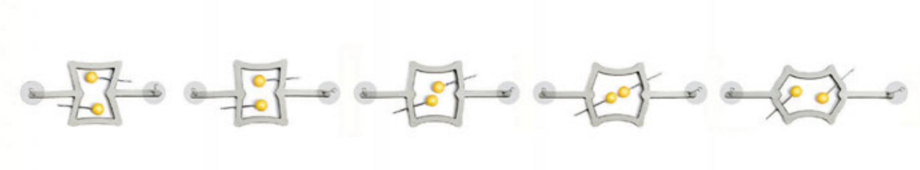

Fig. 3: An inverted hexagonal cell, at increasing stretching, externally fixed to a support (gray circles). The yellow pins showcase the rotation of two opposite inclined walls upon stretching.

Understanding Cell Operation

In more detail, a stretch along the cell's short axis pulls the dart elements apart and makes them rotate (in clockwise direction in fig. 4) until the darts' tips glide past each other. At this point, if the pulling action is removed the dart elements will be in contact and engage mechanically. Once the cell is locked in an open, engaged position, it can resist some compression. A further pulling action will not easily disengage the dart elements because these get in contact with the cells' walls; therefore, a much larger force capable of stretching the walls and making more room for the darts' rotation would be needed. Instead, in order to disengage the cell, it suffices to pull the cell along a different axis (namely, parallel to the engaging surfaces), shearing the cell while exerting a much lower force. More interestingly, if the cell is locked in its open state, it cannot be disengaged easily by pulling it along other directions (see fig. 5), since this would be impeded by the contact between the dart-shaped elements. An interesting aspect is that switching between close and open states is completely reversible, as long as the material used to fabricate the cell is elastic: this allows the programming of the state of the cell, but also the resetting or reprogramming it multiple times. The triangular shape of the dart elements prompts two different orientations for glide and engaging surfaces, and almost automatically suggests how to "operate" the cell to achieve a rest or locked position: and yet, this relationship between shape and behavior was first mediated by a physical experience, and only later extrapolated in geometrical terms.

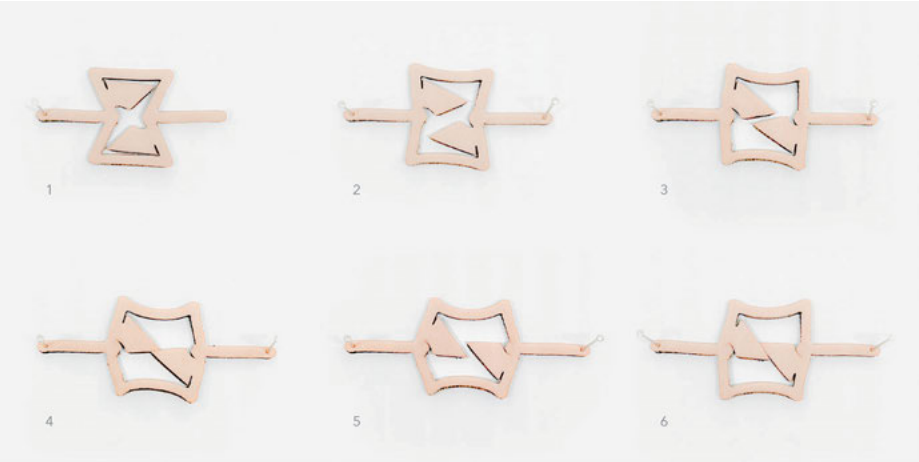

Fig. 4: Image sequence of the cell-with-darts locking mechanism.

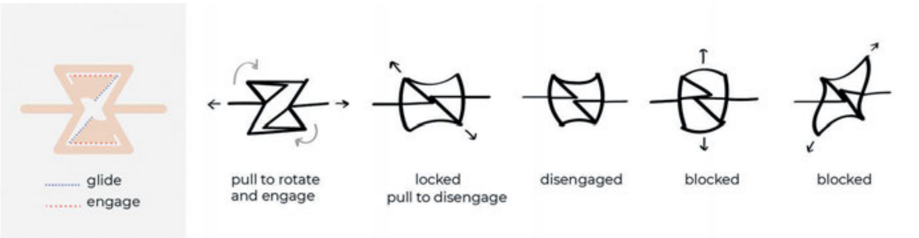

Fig. 5: Possible pulling actions to operate the cell, allowing engagement and locking, disengagement or blocking.

Opportunities in Surface Design

In its open, locked state, the cell has a larger area than in the closed, rest state; at the same time, in the open state, the cell is in a state of self-stress (where the dart elements are in compression while the cell walls are in tension). We took advantage of these two characteristics and fabricated structures composed of many such cells that could be shaped into three-dimensional, stable surfaces (fig. 6). For example, an auxetic sheet composed of mirrored cells grouped into four distinct quadrants morphs into a quadruple dome. Some additional effects can be noticed: the appearance of visual patterning, with continuous bands appearing, which also contribute to stabilizing the domes by increasing the resistance to compression.

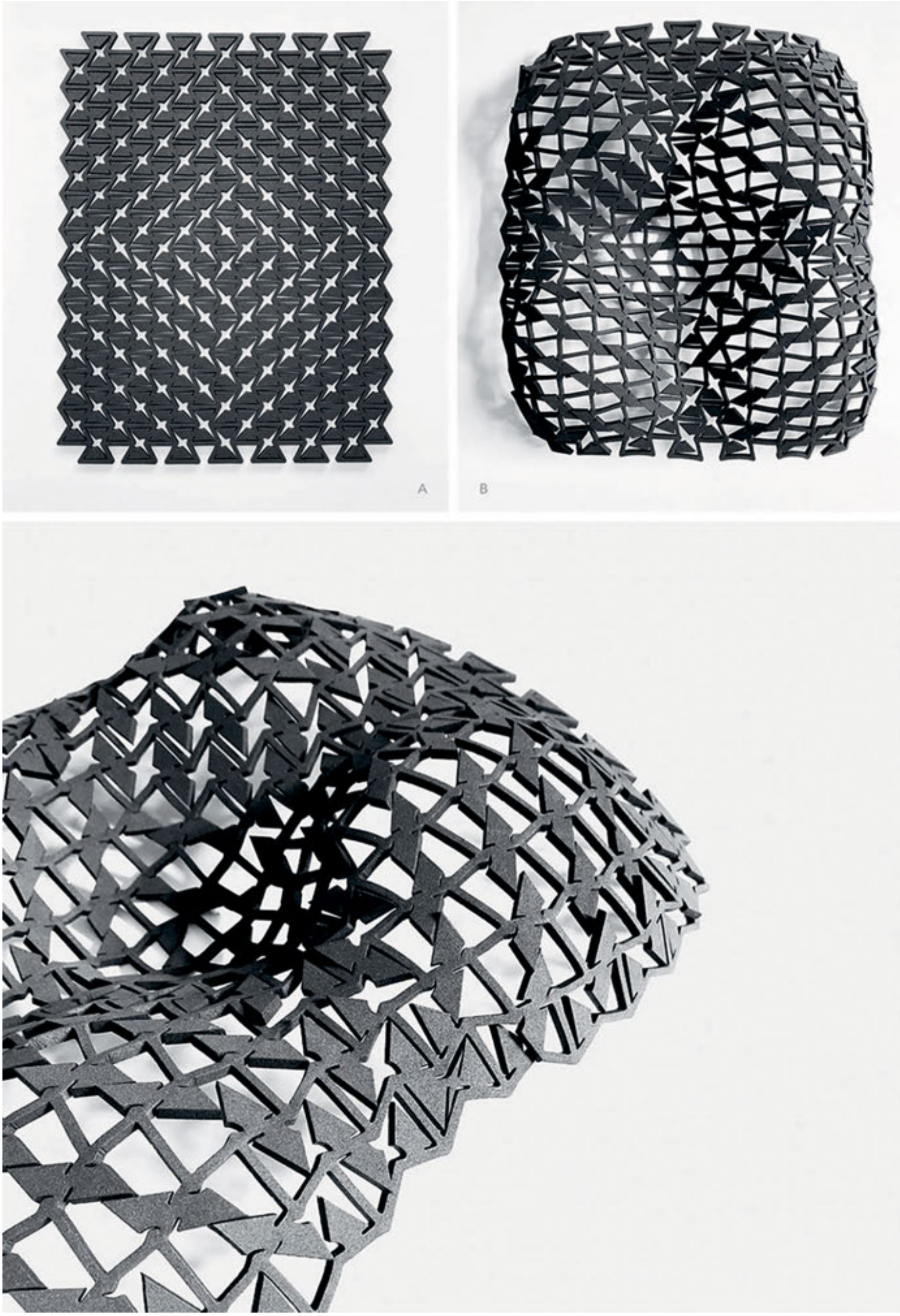

Fig. 6: An auxetic sheet composed of mirrored cells grouped into four distinct quadrants morphing into a quadruple dome.

This opens the way to program—or at least approximate—a target three-dimensional shape into a thin sheet by means of a simple yet quite powerful geometric design at the lower-scale structural units (the inverted cells-with-darts), much like observed in *kirigami* surfaces. What is most interesting about our approach is the possibility to address the stability of the morphed 3D surfaces, a beneficial aspect in architectural scenarios, where the surfaces could be conceived as self-supported structures (bearing their own weight), avoiding external tension or compression elements such as cables or masts.

Edge Activation and Surface Deployment

As the flat-to-spatial morphing in our auxetic sheets needs a local area change taking place during the cell's closed-to-open transition, the individual cells must be stretched. This could be cumbersome or impossible to implement for large structures consisting of many cells. While handling our prototypical surfaces, we realized that individual cells in the sheet interior can be addressed and snapped into the open state by a non-uniform pulling action at the sheet edges, thus activating them at distance (as shown in fig. 7). For example, pulling a square sheet horizontally on its side edges would cause a clockwise rotation of the dart elements. A pulling action on the top and bottom edges instead would cause a counter-clockwise rotation of the dart elements, therefore impeding the cells' transition to the open, locked state. Leaving a segment in the center of the top and bottom edges relaxed allows for the ability to partially remove such a block, resulting in the selective opening of a few cells in the central portion of the sheet.

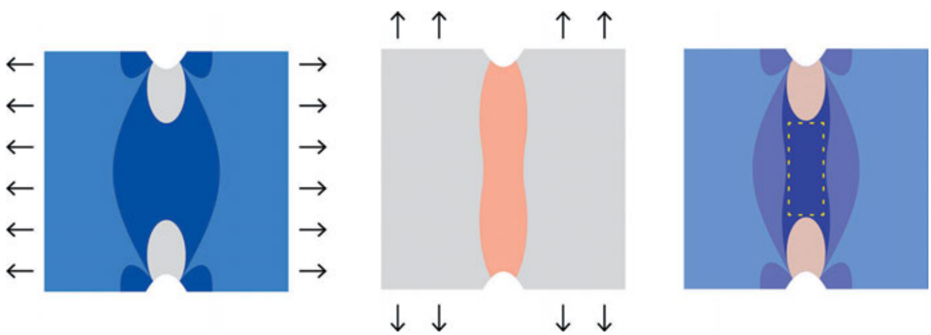

Fig. 7: Edge activation of an auxetic sheet (represented as a continuous square patch) showcasing how to selectively snap open cells at distance by pulling on the sheet's edges. Here, this procedure is targeted at opening only the cells in the sheet's central portion. In the left image, blue areas undergo large horizontal stretching. In the center image, red areas undergo low vertical stretching. In the left and center images, gray color represents areas in which the cells cannot lock in the open state. Therefore, only the cells in the central portion of the sheet—where blue and red areas overlap—will lock in the open state (dashed white rectangle in the right image).

The non-uniform edge activation that we described here could allow the deployment of a free-form architectural surface (e.g., a pavilion) without the need of additional structural support, such as scaffolding. Finally, beyond the evident prospect toward architectural applications already outlined, the specific qualities of the cellular auxetic surfaces we presented can be used to obtain more technical functionalities: for example, creating meta-surfaces with specific transfer of mechanical signals or waves.

An Analogy to Language and Biology

In this hands-on exploration (fig. 8), led by discovery rather than predefinition, we have adopted a trial-and-error strategy, leaning toward geometric features that were of value for us and learning how they influence the structure to fine-tune the in-plane and out-of-plane transformation. This process has led us to design and fabricate auxetic surfaces that can be three-dimensionally programmed, reset, and reprogrammed.

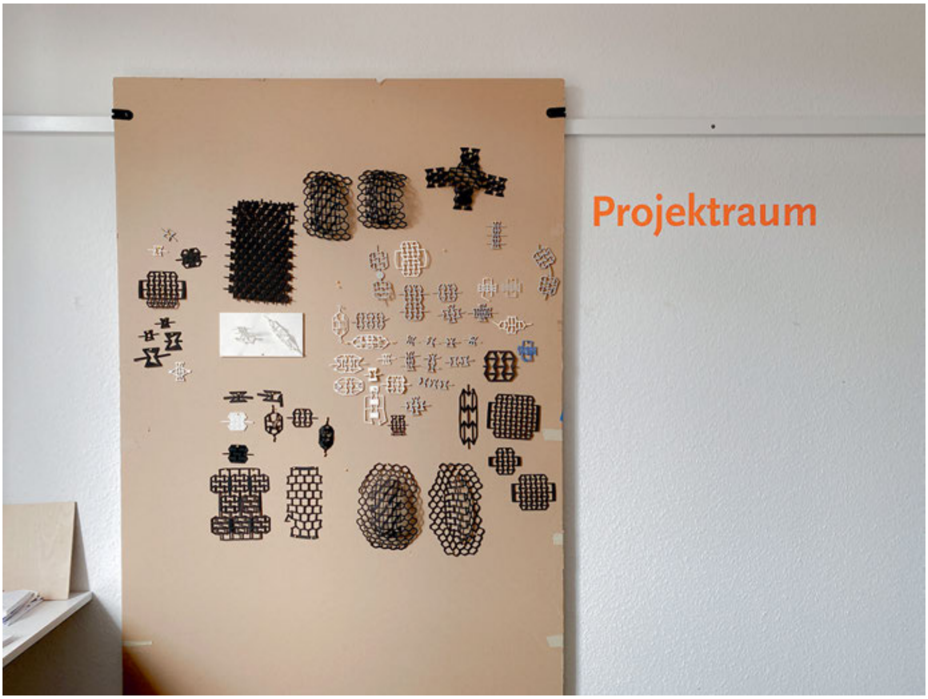

Fig. 8: Physical outcomes of the ongoing research.

Like in biology, certain functions programmed at the cell level can have an effect at a higher, systemic level, creating new, emergent behavior, depending on how cells are assembled.

Tracing a metaphor, the overall process was similar to creating a new language, and then learning how to use it. We first needed to fix the shape of the cells (as letters/symbols) and identify a set of geometric rules to operate them (as a “material grammar”). The single cells are then put together into a spatial arrangement of periodic structures that can transform and create complex morphing, just like letters are assembled into words and create meaningful sentences through grammar. Moreover, some additional visual and sound patterns emerged as bound to this specific material, just like idiomatic expressions are situated in a specific language.