ARTISTS' ARTICLE

# Artistic Exploration of the Worlds of Digital Developmental Swarms

*Sebastian von Mammen, Thomas Wißmeier, Joyce Wong and Christian Jacob*

ABSTRACT

This paper presents artwork that was inspired by a computational model called Swarm Grammars. In this work, the "liveliness" of swarms is combined with the generative capabilities of more established developmental representations. Three of the authors followed their individual artistic approaches to explore the creativity and dynamics of Swarm Grammar structures. One chose to breed structures interactively to compose virtual spaces. The second explores the movement and construction dynamics of interactive swarms. The third artist translated developmental processes of Swarm Grammars into interactions of paint particles driven by friction and gravity.

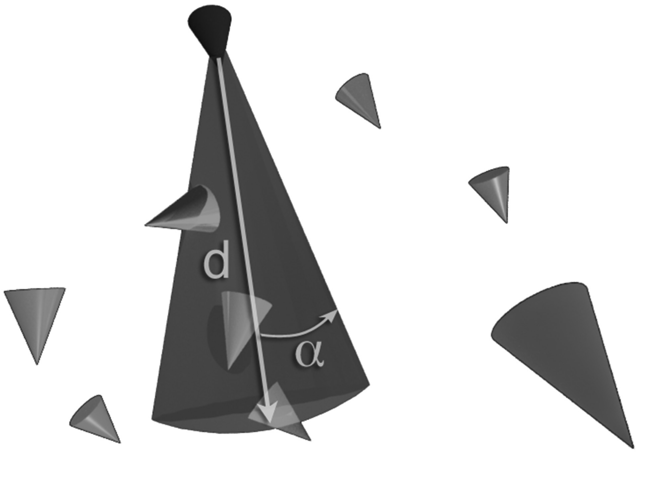
With an open mind and open eyes, we discover breathtaking forms and colors, textures and shapes in nature. The ridged desert sands, the reflection of the sun on the sea, or serene alpine landscapes have served as motifs for countless paintings, pictures and movies. Nature's glamorous constituents of organic origin, such as butterflies and shells, have been collected for their beauty over centuries. Through algorithms that retrace the processes of growth in plants and other forms of life we can also produce beauty. Indeed, digital art has grown far beyond a binary heritage that is only suited to re-shaping the reflections of real objects or creatures.

Algorithms can simply implement nature-inspired processes of growth and development by repeated substitution of symbols in a string according to a set of rules. L-Systems, which do exactly this, can simulate the growth of cells [1], plants [2], organs [3] and architectural designs [4]. From a larger perspective, generative processes or developmental models have extended the computational realms of creation and creativity [5].

Besides the distinction of individual symbols, e.g. A or B, any information about the relations among the replicating units has to be inferred from the L-Systems' strings by an external interpreter. Co-authors Sebastian von Mammen and Christian Jacob have designed Swarm Grammars as a novel computational representation and algorithmic approach to simulated growth. In Swarm Grammars, complex networks of relationships develop because Swarm Grammars combine the developmental aspect of L-Systems with an agent-based modeling approach [6]. Each symbol is considered an individual that perceives and reacts to stimuli in its environment while grammatical rules drive its reproduction and construction processes. Thus, highly dynamic, complex networks of interactions emerge [7].

The Swarm Grammar examples in this article combine the coordination of movement as seen in birds, reproduction as modeled in the growth of cell colonies or plants and the indirect communication through the environment used by social insects. These aspects are found in many natural systems, e.g. chemotaxis, quorum sensing and bio-film aggregation at the cellular level. Algorithmically, those aspects have mainly been studied independently. We utilize Swarm Grammars that combine these aspects to create life-like artifacts that both resemble organic forms [8] and capture the dynamics of the construction processes [9].

**Fig. 1. All mates within the conic field of perception of the dark agent are considered its neighbors. The perception range is determined by a distance d and an angle α. (© Sebastian von Mammen)**

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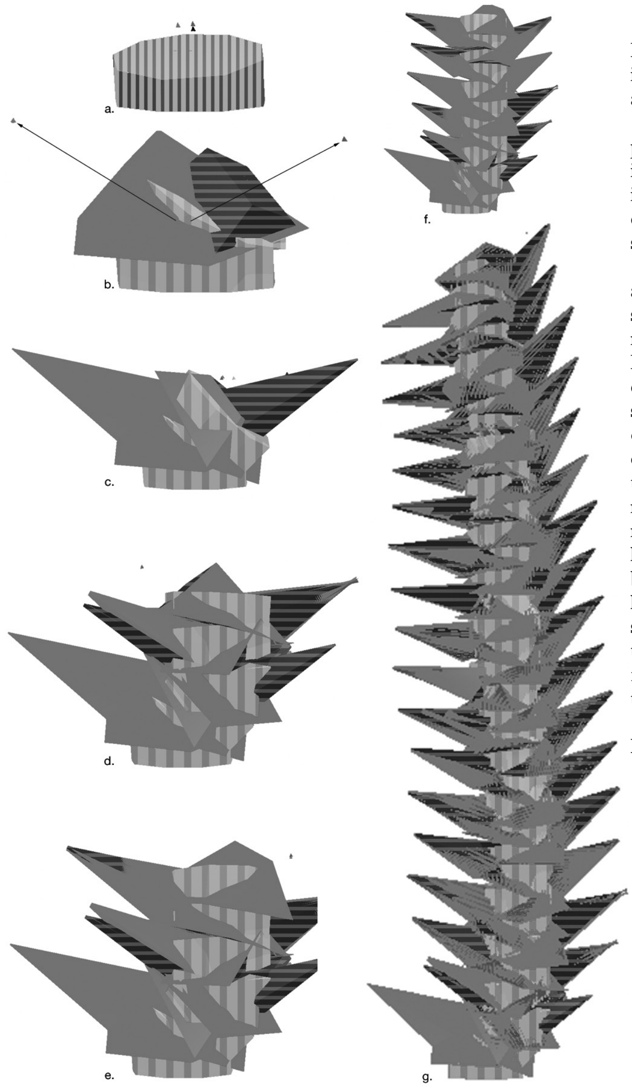



**Fig. 2. Swarm Grammars in Action: (a) Three agents, A, B, and C (represented as small pyramids), are heading upwards after their initialization. Agent A creates the vertically striped centered stem. (b) Agents B and C drift apart (indicated by the slim arrows). Before they run out of energy, agents B and C create the spiky construction elements seen in (c). The spikes occur because the agents' energy levels are linked to their construction elements' diameters. In the meantime, agent A, often hidden from the camera by construction elements, has produced new offspring and the construction module created so far is repeatedly added to the growing structure (d–g). (© Sebastian von Mammen)**

While artists and computer scientists have explored computational developmental models and artificial swarms to a large extent, the exploration of Swarm Grammars has begun only very recently. Nest constructions by social insects such as wasps, ants and termites hint at the power of swarm-based developmental models. In this paper we present the works of three artists—the paper's co-authors Sebastian von Mammen, Thomas Wißmeier and Joyce Wong—who work from Swarm Grammar structures to create real-world artworks. Their works relied on simulations and simulation tools conceptualized by co-authors von Mammen and Jacob. The section "Creating Space" discusses von Mammen's utilization of Swarm Grammars to create artificial spaces. In the section "Abstraction of Dynamics," Wong offers a window into the inspirational manifestations of interaction dynamics in complex systems. Finally, in "Models as Basis for Experiments," Wißmeier looks at how the artworks serve as visionary playgrounds for artistic expression, media and forms. In the conclusion we provide an outlook on possible future work.

## Related Work

Machines help us in performing repetitive tasks. The more powerful the machine, the more complex the conductible action can be. Analogously, a more powerful, expressive and abstract computational representation often yields more complex computable results. Multi-cellular organisms are outstandingly complex systems. With L-Systems, Lindenmayer successfully found a grammatical representation for the growth of clusters of cells [10]. In retracing the development in natural systems, L-Systems can create natural aesthetics. Based on L-Systems and other mathematical methods—including fractals—intriguing sculptures of artificial aesthetics can be evolved [11]. Whole worlds of seemingly living organisms can be made to grow in virtual spaces [12].

An important aspect of developmental systems is their ability to evolve. Real creativity is conjured when computational evolution drives the development of structural and graphical representations. A human "breeder" can manually select "fit" individuals [13,14]. Alternatively, automatic evolutionary runs can foster structural attributes that optimize mathematical fitness measures, e.g. for increasing design complexity [15] or to introduce architectural functionality. In an attempt to automate the evaluation of generated computer art, human-made works can provide reference points for assessments. The combination of computational evolution and developmental models has produced many artistic works; see for example Part III in The Art of Artificial Evolution: A Handbook on Evolutionary Art and Music by Romero and Machado [16]. However, artificial life methodologies have instilled other important aspects in computer arts. Artificial swarms, for instance, regularly enthuse public audiences in interactive art installations [17]. Through the interactions of large numbers of flocking individuals, or boids (see Reynolds [18]), a certain "liveliness" is communicated. As an underlying principle, each swarm individual (referring to a single unit of the swarm) has a limited perceptional field that determines its neighborhood. In Fig. 1 the field of perception is defined by the viewing distance d and the angle $\alpha$. Furthermore, at each time-step of the simulation, the individual computes its current acceleration in accordance with its neighbors. As a consequence, the individual changes its position and its neighborhood configuration, as do the neighboring flock mates. Hence, a feedback loop of interactions is triggered that can lead to a variety of flocking behaviors [19].

Primarily, the flocking dynamics of artificial swarms feed into animations. But the spatio-temporal interaction network of swarms also supports computational music generation [20]. Furthermore, simply by leaving traces in space, the flocking patterns can be "solidified" and their dynamics captured in virtual 3D sculptures. Some of these virtual sculptures have served as inspirations for traditionally crafted collages and paintings [21].

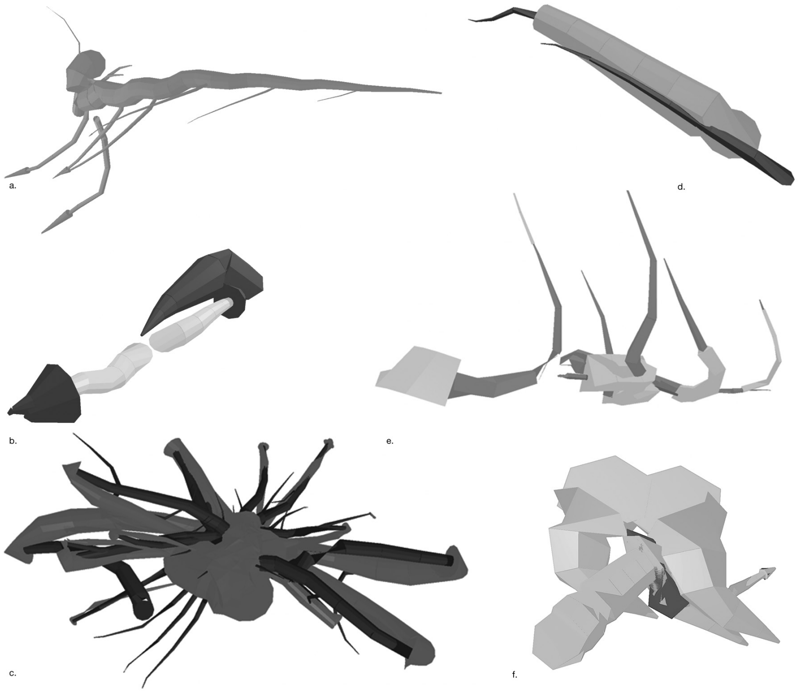


**Fig. 3. Evolved Swarm Grammar Samples. (© Sebastian von Mammen)**

## DEVELOPMENTAL CREATIVITY OF SWARMS

When termites build their nests, they do not work from a blueprint of the new construction. Instead, they follow their instinct and build wherever they see fit. In fact, the construction activities of social insects are determined by pheromone trails left by other individuals, construction cues in their immediate environment, physical gradients such as heat and humidity, or by plain chance. Based on this idea, simple sets of probabilistic behavioral rules have led to constructions similar to those observed with ants and wasps [22].

Swarm Grammars are a computational concept that integrates (1) the power of constructive swarms with (2) the ability to instantaneously reproduce and (3) the boid flocking paradigm outlined earlier. Figure 2 shows an example of Swarm Grammar development. In Figs 2a through 2g Swarm Grammar agents split and leave construction elements along their flocking paths. The depicted Swarm Grammar hosts three agent types, A, B and C, each exhibiting a different flocking behavior and leaving different construction elements along its path. With an initial, "axiomatic" agent, A, reproduction is performed according to the rule-set $\{A \rightarrow ABC, B \rightarrow A, C \rightarrow AA\}$. In Fig. 2a, a construction element has been placed by an agent of type A. Already, the first production rule has been executed, leaving three agents A, B, C, illustrated as the small pyramids floating at the top of the construction. Subsequently, in Figs 2b to 2g the reproduction and construction process continues: Agents B and C quickly drift apart (emphasized by the two arrows in Fig. 2b), losing most of their internal energy. The loss of energy is reflected in the shrinking diameter of their constructions. Hence, after another reproduction on each side, the construction processes stop. Only the initial agent A keeps enough energy for persisting cycles of reproduction and construction. In the Swarm Grammar configuration used, the loss of energy is type-dependent and linked to the agents' movements and replication processes. The rules for reproduction and differentiation are triggered after a type-dependent interval of simulated steps.

**Fig. 4. Diptych of the two pieces (b) *caméléon* and (c) *bighorn sheep* by Sebastian von Mammen, acrylic medium on canvas, 23 × 38 inches, 2008. Selections of Swarm Grammar structures bred for the diptych are displayed in (a) and (d), respectively. (© Sebastian von Mammen)**

Different sculptures emerge when we change the reproduction rules and the agent properties (Fig. 3). We can change this Swarm Grammar configuration manually or by means of computational evolution. Many approaches have been tested for the latter case:

1. Through interactive evolution an external breeder rates an array of Swarm Grammars [23].
2. In an immersive (co-)evolution approach a "gardener" tinkers with Swarm Grammars in a virtual space by replenishing their energy to further their growth, by inducing mutations or by crossbreeding selected specimens [24].
3. Using automatic evolution a fitness measure is formulated mathematically, which serves to evaluate the construction processes and the emerging structure [25].

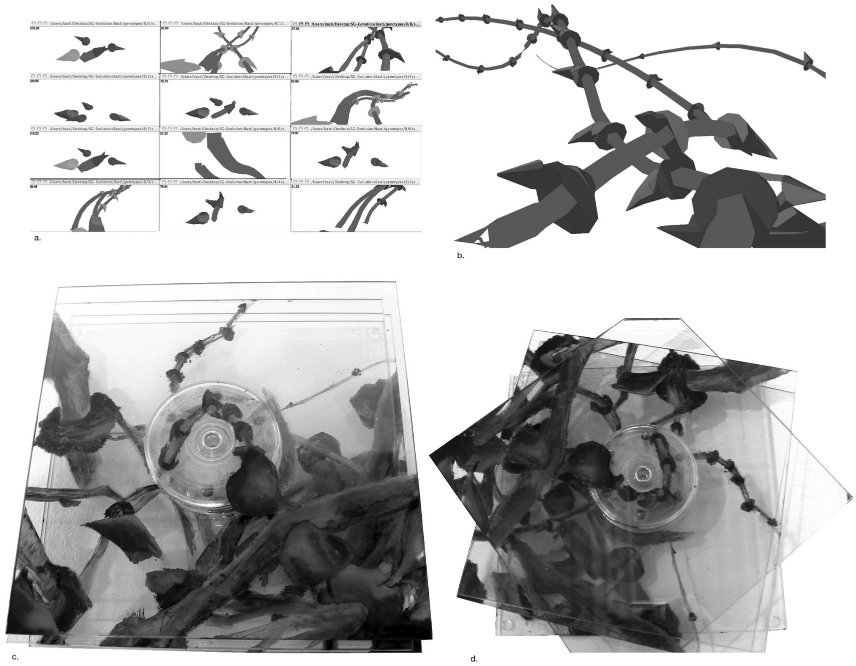


**Fig. 5. During an interactive evolutionary run (a), the depicted rose-like structure emerged (b). (© Sebastian von Mammen) This structure inspired the piece *Pirouette in Red* by Joyce Wong, 12 × 12 inches, acrylic and oil on glass, 2008: (c) the sculpture in its initial position; (d) bearings allow the plates to rotate into different configurations. (© Joyce Wong)**

## Creating Spaces

Stimulated by the architectural capabilities of Swarm Grammars, artist-author Sebastian von Mammen combined a collection of swarm structures to create surreal, artificial worlds. In about 40 interactive evolutionary experiments, von Mammen bred the utilized Swarm Grammar structures relying on Christian Jacob's Mathematica library Evolvica for the evolutionary algorithm [26] and the user interface Inspirica [27]. The breeding experiments yielded the sets of Swarm Grammar structures displayed in Figs 4a and 4d. In the corresponding paintings, Figs 4b and c, respectively (see also Color Plate A), a chameleon and a bighorn sheep are immersed in complementary artificial environments.

During the evolutionary runs, von Mammen followed two main objectives. First, robust-looking beams should emerge to form a structural mesh, thus opening vast spaces by their mere existence. Second, fuzziness, continuity and resemblance are sought to warrant the authenticity of the generated virtual worlds. The color gradients in the backgrounds reflect the extreme climates of the habitats of the portrayed animals. They also highlight the wholesome, fluent structural architecture in Fig. 4b (see also Color Plate A), and the liveliness and dynamics caught in the erratic structures of Fig. 4c, with "warm" and "cold" palettes, respectively.

## Abstraction of Dynamics

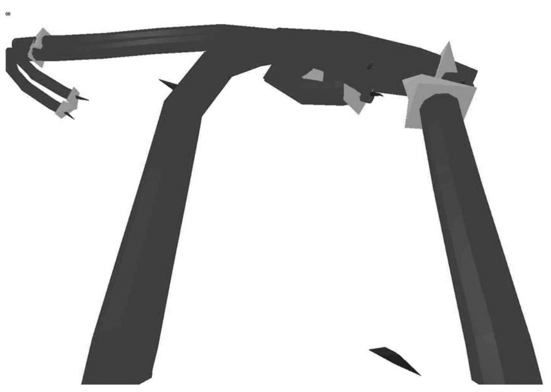
The smooth, interwoven curves with sporadically grown thorns seen in Figs 5a and 5b emphasize the emergent flocking dynamics of the constructing Swarm Grammar. Figure 5a shows a screenshot from the interactive breeding procedure: Several specimens are growing according to their configuration, independently in isolated spaces. After close inspection, the external breeder, in this case the team of Wong and von Mammen, rates present Swarm Grammars. Based on their received fitnesses, individuals are selected for the next generation of Swarm Grammar simulations. During the transition from one generation to the next, a certain percentage of selected Swarm Grammars are interbred to combine some of their characteristics. The so-called mutation operator introduces small configuration changes to some of the other selected specimens.

Artist Joyce Wong chose the Swarm Grammar structure depicted in Fig. 5b to inspire her real-world sculpture shown in Figs 5c and 5d (see also Color Plate A). Four glass plates, painted with matching Swarm Grammar graphics, are connected through bearings that allow them to turn (Fig. 5d; see also Color Plate A).

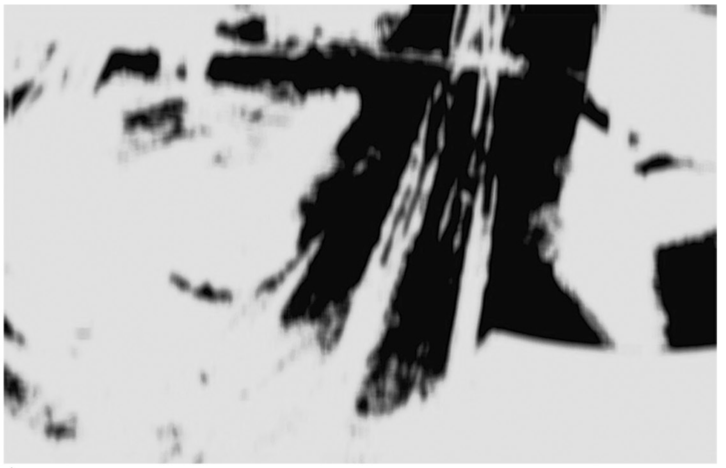
Through this innovative sculptural design, the dynamics of the Swarm Grammar growth processes are maintained. The interdependent flocking of the Swarm Grammar agents can be replayed by rotating the glass plates, causing a great number of alternative structures of the same constituents to emerge. The layer-wise mapping of a two-dimensional image results in a fully 3D sculpture. Both the glass plates and the bearings have a significant height (about 0.3 inches). Hence, although the images are flat as on a computer screen, they materialize as if they are three-dimensional due to the interplay of transparent plates and bearings.

## Models as Basis for Experiments

Publishing about art inherently requires photographs to show the discussed pieces. Artist Thomas Wißmeier, however, intentionally chose the medium of photography for another reason. Photography supports Wißmeier's experimental work with an immense degree of freedom, particularly the works based on sculptures presented at the end of this section. As pointed out by the Austrian arts professor Christian Reder [28]: "As a multitude of considerations, pictures, layers, associations, the model is always a working model at the same time." This statement is a creative imperative—to



a.



b.

**Fig. 6. (a) Swarm Grammar sculpture (© Sebastian von Mammen) that provided inspiration for (b) Thomas Wißmeier, *Gate*, acrylic media on wood, 22.4 × 39.4 in, 2008. (© Thomas Wißmeier)**

use the model is to work with it and to improve on it; it is not an effort of chasing the initial idea to its immediate finalization. In the context of the presented work, we follow several iterations of a self-similar methodological approach: Scientific biological models were unified by Swarm Grammars, a computational (meta-)model of developmental processes. In a second step, unfolding an instance in the computational model space led to 3D structures in virtual space that served as models for artistic work.

## Translating between Virtual Spaces

The Swarm Grammar sculpture of Fig. 6a has been captured by the artist in a rather abstract fashion in the photograph shown in Fig. 6b: With monochromatic coloring and extrapolation the artwork goes beyond the original structure by adding a third column. Like the art pieces presented in the "Creating Spaces" section, the photograph accentuates the architectural characteristics of some Swarm Grammar structures. But even though the stylized elements were reduced in number, the architectural and sculptural features of the original structure are strengthened. Wißmeier painted the underlying material piece with varnish on a large wooden panel and smoothened the strong contrasts and hard edges in order to facilitate in viewers an engagement with the photograph's spatial aspects.

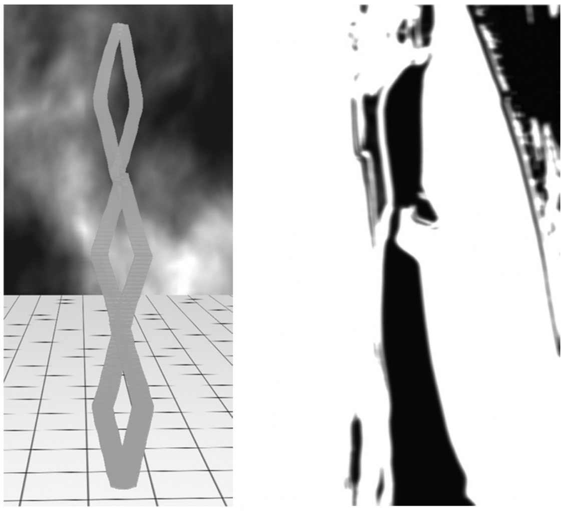
The Swarm Grammar structure in Fig. 7a inspired Wißmeier's photograph in Fig. 7b. The photograph is the result of an intricate experimental process: A glass plate was primed on one side; on the other side varnish was applied with a sponge in a subtle manner and reworked with shades of white and blue; in addition, undesired light reflections, which occur in photographs when working with varnish, were removed. The piece reflects the similarity between Swarm Grammar structures and clouds. Clouds, too, are spatial structures that continuously change.

The same process led Wißmeier from the Swarm Grammar structure in Fig. 8a to the unnamed photograph displayed in Fig. 8b. Rhythmic collisions in the Swarm Grammar sculpture emerged through synchronized differentiation into swarm agents that attract and re-

**Fig. 7. Inspired by the semi-transparent branching Swarm Grammar structure in (a) (© Sebastian von Mammen), Thomas Wißmeier used experimental processes involving painting with mixed media and reworked photographs to create (b) Thomas Wißmeier, *Cloud*, acrylic media on wood, 2008. (© Thomas Wißmeier)**

a.

b.



a. b.

**Fig. 8. The Swarm Grammar structure shown in (a) emerged from the interactions of swarm agents attracting and repelling one another. (© Sebastian von Mammen) Inspired by the process at play in (a), Thomas Wißmeier worked with black and white color compounds having enough surface tension to repel each other, thus competing for surface space on this 17.3 × 25.2 inch glass plate (b), acrylic media on wood, 2008. (© Thomas Wißmeier)**

pel each other. The resulting structure arose from a competition between repelling color compounds. Black and white colors competed for surface space on a glass plate. This competition came about through a thinning of the varnish that allowed it to flow quickly with gravity. At the same time, the compounds retained enough surface tension to repel each other.

Allowing color particles to find their own paths is very similar to the idea of autonomous Swarm Grammar agents leaving traces in space. To further explore this idea, Wißmeier emulated the branching processes that led to the Swarm Grammar sculpture depicted in Fig. 9a to create the work shown in Fig. 9b, in which he used a finish with a thick texture on a sloped wood panel with a coarse surface; the effects of gravity propelled the color particles to disperse across the surface. Moreover, Wißmeier rotated the piece, causing the color to run in different directions. Thereby, the artist only indirectly affected the outcome.

## Finding the In-between World

In the works we present in this section, the Swarm Grammar sculptures were used as inspirational starting points for real sculptures. A newly gained spatiality fully springs to life in the pieces in Figs 10b and 11b (see also Color Plate A). The interplay of light and shade creates deep, smooth textures, provoking tactile urges. The photographs convey an organic look and the fuzziness that we know from natural phenomena. The pieces look soft and gnarly, like skin, but have their very own unique structures.

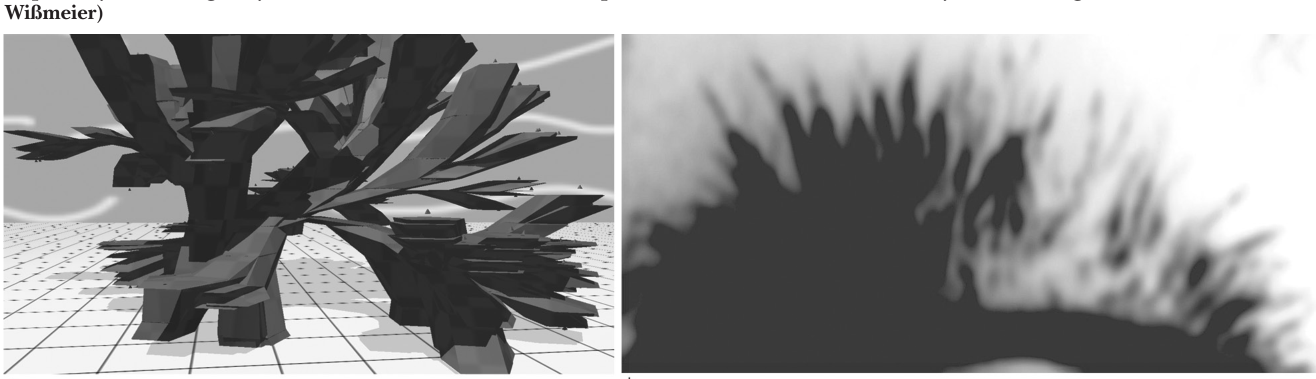
Figure 10a shows a Swarm Grammar structure with a compact yet spiky core to the right-hand side and seven thick, entangling outgrowths. Their regular segmentation and their pointy ends capture the viewer's attention. Inspired by this virtual sculpture, Wißmeier chose wires and tin foil as construction elements for a corresponding real-world model. These materials were chosen to mimic the compact wrappings and outgrowths of the Swarm Grammar sculpture. Although the original swarm structure is not directly identifiable in the photograph (Fig. 10b), several analogies are evident:

1. The partition of the aperture: few light elements on the left-hand side and impenetrable surfaces to the right.
2. Interwoven offshoots to the left and a protruding one in the top-right pane.
3. A rippling spiral similar to the segmented outgrowths in the Swarm Grammar structure.

Most importantly, however, very general, common features stand out. First, the unity and the role of the interwoven elements are apparent. Second, the smoothness and the dynamics of the sculpture are also noteworthy.

Searching for other suitable materials to simulate Swarm Grammar processes, Wißmeier relied on paper for the piece presented in Fig. 11b (see also Color Plate A). A soft light reflection is introduced through the material. The swirly twist of the Swarm Grammar agent illustrated in Fig. 11a is directly reproduced in the sculpture in a manifold way. In this case a craggy, concave surface was devised. The radial gradients in combination with the fuzziness of the photograph create the impression of circular motion. The white background of the simulation screenshot was turned into black for the photograph, spotlighting the sculpture and allowing for an adroit illumination.

**Fig. 9. Inspired by the Swarm Grammar structure shown in (a) (© Sebastian von Mammen), Thomas Wißmeier caused color particles to disperse by means of gravity across a coarse 13.8-×-27.6-in wood panel to create (b) the work *Blue*, acrylic media on glass, 2008. (© Thomas Wißmeier)**



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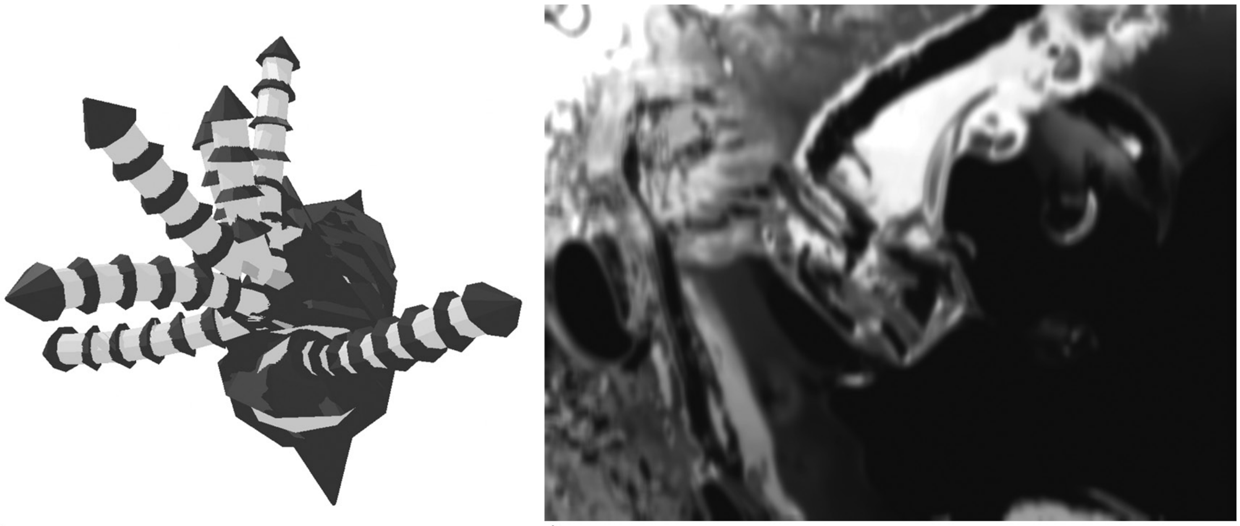

a. b.

**Fig. 10. The Swarm Grammar structure shown in (a) (© Sebastian von Mammen) inspired Thomas Wißmeier's sculpture (b), clear varnish, acrylic media, tin foil, mixed media (acrylic, varnish, wood, glass, tin foil, wires, paper), 7.9 × 9.4 × 2.8 in, 2008. (© Thomas Wißmeier)**

## Summary and Future Work

Scientists and artists have collaborated in producing the interdisciplinary work discussed in this paper. We believe that these pieces both enrich the art world and can inspire those involved with making models on any level of abstraction—in silico, in vivo or in-between.

In the future, we want to refine several concepts and approaches. The applied Swarm Grammar model is still restrictive in many ways: The assortment of construction elements is very small, limiting imaginative possibilities. Broader selections and more intricate shapes could enhance the artistic value of the swarm-built structures. Due to the overwhelming number of parameters that determine a Swarm Grammar construction, the only way currently to implement and realize a conception is through computational evolution. Although we believe in the power of this approach, a working artist expects greater freedom for individual arrangements in many cases. Therefore, embedding an interactive design tool into the Swarm Grammar simulation framework would be beneficial.

Regarding new concepts for Swarm Grammar art, we are currently developing mechanisms for the self-organized assembly of 3D structures, following the idea of autonomous color particle paintings. In order to do this, the stepwise extension of the particles' attributes in tandem with means to affect the particles' situations and interactions needs to be investigated. As a starting point, we rely on layering propelled color particles—inspired by some of the early works by Canadian artist Gerald Hushlak [29] as well as Wong's sculpture *Pirouette in Red* (Fig. 5) and Wißmeier's photographs seen in Figs 8b and 9b. A series of photographs of experimental trials by von Mammen is displayed in Fig. 12. Although this approach has similarities to modern 3D plotting devices [30] and feeds on real-world experiments on self-assembly [31], we believe that the swarm perspective provides a playground for novel ideas.

### Acknowledgments

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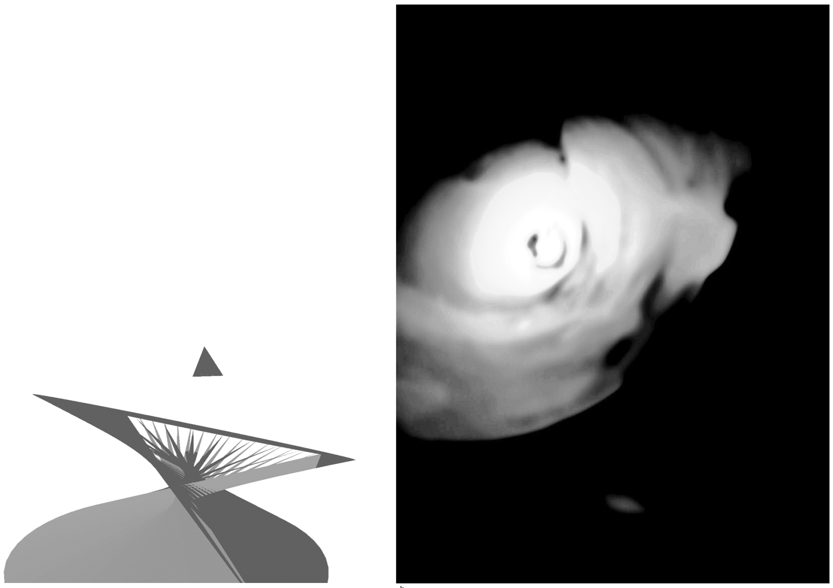
**Fig. 11. (a) Swarm Grammar graphic (© Sebastian von Mammen), which served as inspiration for (b) Wißmeier's swarms formed from acrylic media on paper, 2008. (© Thomas Wißmeier)**



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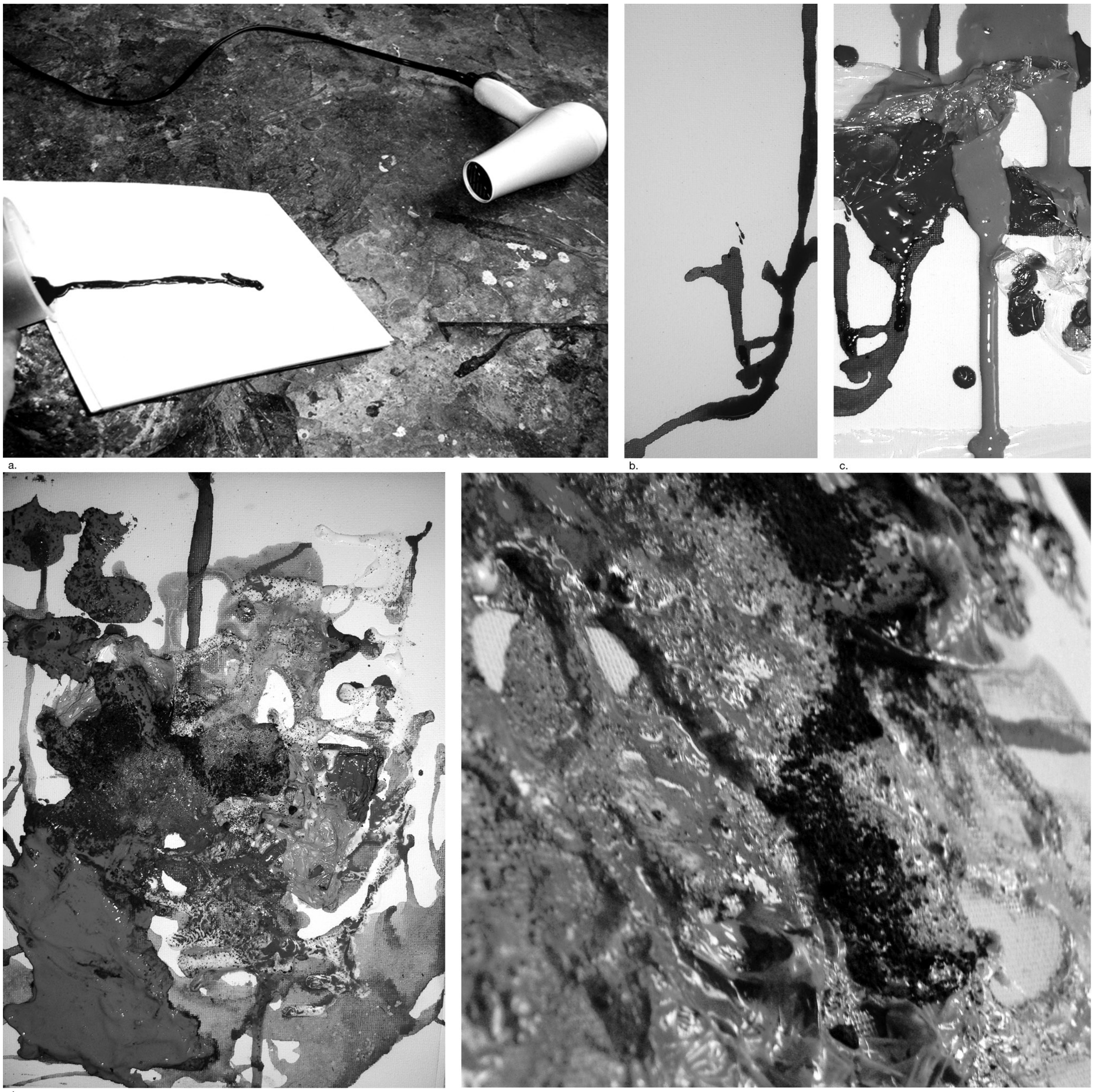


**Fig. 12. Series of photographs showing developmental swarm structures: (a) While color runs down a sloped canvas, a dryer is used to counter the effects of gravity by blowing upwards; (b) The interplay of forces creates branching structures; (c) New layers of color and plastic foil are introduced into the artificially created physical world; (d) Complex structural relationships emerge through the interacting layers of mixed media; (e) The emergent texture has grown into three dimensions. (© Sebastian von Mammen)**

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