Swarm Art

Gary Greenfield and
Penousal Machado

ABSTRACT

Gary Greenfield and Penousal Machado, the curators behind the Leonardo Swarm Art Gallery, introduce the works of the artists featured in the Gallery, who explore, experiment with and engage with the behavioral principles underlying swarms. Greenfield and Machado's introduction provides a tour of some of the historical highlights in the development of "swarm art" and reveals the broad range of methods that appear within the genre.

In 1986, Craig Reynolds formulated a simple but elegant model to simulate the flocking behavior of birds [1]. His implementation, called Boids, had a profound and lasting impact on both computer graphics and artificial life [2]. His original model has since been extended to many other social species, including bees, ants, bats and fish. The basic concepts are fundamental for modeling and simulating migration, schooling, foraging, crowds, herds and swarms. Applications abound in computer-generated special effects, gaming, optimization and visualization.

Since the turn of the 21st century, artworks involving the behavioral principles underlying swarms have coalesced under the generic label "swarm art." Such artworks examine issues related to self-organization, communication, behavior and interaction. It is daunting to try and trace the definitive origins or history of swarm art, so what follows can be described as at best a brief tour of some of its highlights, as well as a guide to the artwork we have assembled here.

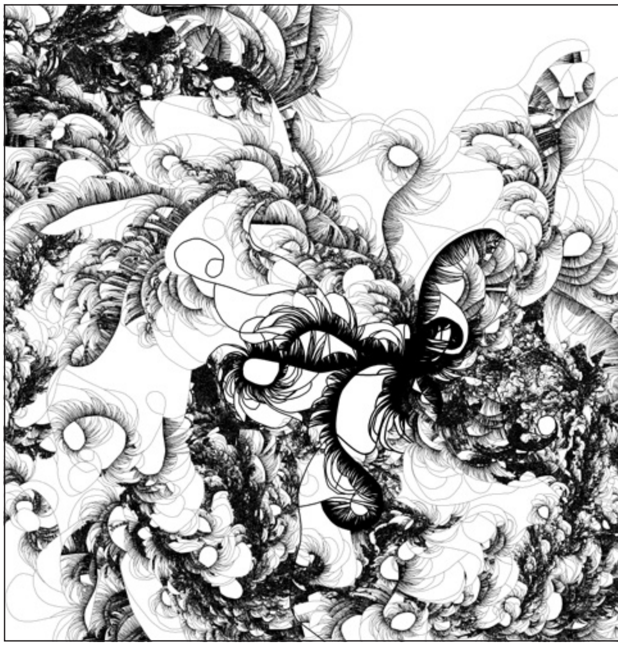
The interactive art and audio installation *Relazioni Emergenti* by Mauro Annunziato, featured in the SIGGRAPH 2000 Art Gallery [3,4], consisted of an artificial life environment whose digital inhabitants competed for territory by marking it with curving trails, called "filaments," and by generating offspring to continue the endeavor. In 2001, the work won an Honorable Mention in the Vida Life 4.0 Art and Artificial Life Competition [5]. Its precursor, *The Nagual Experiment* [6], created patterns that were the effect of the self-organization of a population of individuals during their development and growth. Figure 1 shows a pattern from *The Nagual Experiment*, and Color Plate C shows a screen capture from *Relazioni Emergenti*.

In 2002, at the Telfair Museum's Jepson Center, Daniel Shiffman exhibited his interactive video installation *Swarm*, featuring a collection of virtual agents behaving according to principles similar to Reynolds's Boids post-processes; the work displayed video captured in real time [7]. This installation was showcased at SIGGRAPH 2004 [8]. Further continuing in the tradition of Boids, in 2004 Christian Jacob and Gerald Hushlak initiated their *SwarmArt* project, which yielded 3D swarm art visualizations and artwork [9]. In 2006 they announced its follow-up, *SwarmPainter* [10].

So-called ant paintings were first introduced by Nicolas Monmarché in 2003 [11] as an attempt to find a more expressive way to understand and explain the ant algorithms that were then being developed by ant colony optimization researchers. In 2004, Tim Barrass began exploring the artistic potential of modeling ant behavior using neural nets. An example of his impressive video was included in the 2006 EvoMUSART art show [12] and has also been posted on-line [13]. Using a stricter biological interpretation coupled with the help of evolutionary algorithms, Gary Greenfield [14,15] and Paulo Urbano [16] have further developed ant paintings. Their efforts concentrate on faithfully modeling ant behavior in conjunction with ants' use of pheromones.

In the realm of non-photorealistic rendering, Yann Semet, Fredo Durand and Una-May O'Reilly combined image-processing techniques with ant colony simulation methods to

Fig. 1. Mauro Annunziato, *The Nagual Experiment*, digital image, 1998. (© M. Annunziato)



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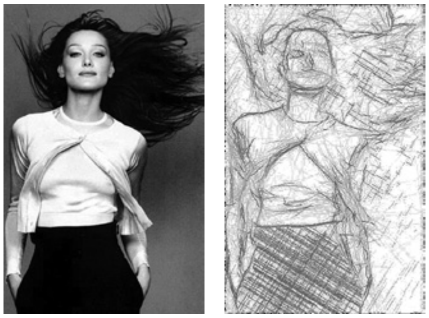

Fig. 2. (left) Photo of Carla Bruni (photographer unknown). (right) Y. Semet, F. Durand and U.-M. O'Reilly, *Carla Drawing #2*, swarm art line drawing, 329 × 509 pixels, 2002. Printed with permission. (© Yann Semet, Fredo Durand and Una-May O'Reilly)

create swarm art [17]. What distinguishes their work is the use of swarms to yield representational, as opposed to abstract, imagery derived from photographs. Figure 2 shows an example resulting from configuring their virtual swarm to produce line drawings from black-and-white photographs. In 2010, Carlos Fernandes [18] also simulated swarms of ants in his non-photorealistic rendering system *Pherographia*, which transforms black-and-white images into ant pheromone distributions. In 2012, Penousal Machado and Luis Pereira [19] used an approach similar to that of Semet et al. to produce abstract, non-photorealistic ant paintings from color photographs.

Ant species use a variety of sensory capabilities and mechanisms other than pheromones to regulate behavior. In this regard, Urbano has leveraged the nest-building behavior of the ant species *T. albipennis* to make ant paintings [20], while Greenfield has capitalized on the seed-foraging behavior of the ant species *P. barbatus* to the same end [21].

In 2010, Alice Eldridge exhibited the generative swarm art work *You Pretty Little Flocker* [22,23] in digital print form at the British Science Festival in Birmingham, U.K., as an animation at the Computational Aesthetics exhibition in Carcavelos, Portugal, and at the Guildford Lane Gallery in Melbourne, Australia. To complete our whirlwind tour, and to come full circle, taking up where Annunziato left off, in 2009 Jon McCormack [24] drew from ecology and generative art to develop an evolutionary drawing ecosystem that produced drawings such as the two shown in Fig. 3, based on swarm art principles.

We are grateful to Mauro Annunziato, Yann Semet and Jon McCormack for granting us permission to include examples of their artwork in this introduction and to Tim Barrass, Alice Eldridge, Christian Jacob, Nicolas Monmarché, Una-May O'Reilly, Daniel Shiffman and Paulo Urbano for accepting our invitation to participate in this *Leonardo* Gallery. We hope readers will find the artwork compelling, complex and reflective of the myriad of rich and diverse interactive behaviors that swarms are capable of exhibiting.

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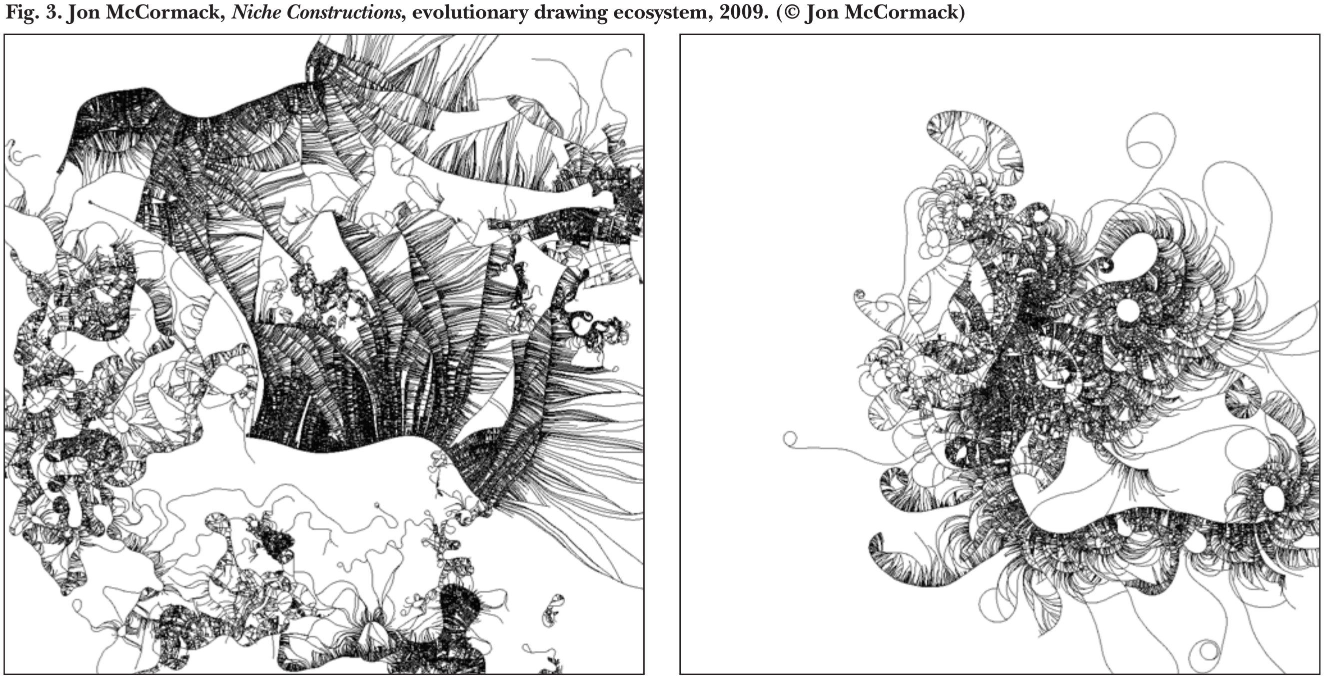
Fig. 3. Jon McCormack, *Niche Constructions*, evolutionary drawing ecosystem, 2009. (© Jon McCormack)



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Gary Greenfield is Professor Emeritus of Mathematics and Computer Science at the University of Richmond. His research interests include algorithmic art, evolutionary computation, artificial life, cryptography and division algebras. He is the author of more than 50 refereed journal and conference papers in these areas and has co-organized as well as been a member of the Program Committee for many conferences. He is the founding editor of the Journal of Mathematics and the Arts and has been a regular contributor to math-art exhibitions since 1998. Recently, he assumed the post of Artistic Director for the Museum of Mathematics (MOMATH).

Penousal Machado teaches Artificial Intelligence and Computational Art at the University of Coimbra and is a senior researcher in the Cognitive and Media Systems group of the Centre of Informatics and Systems at the University of Coimbra. His research interests include computational art and design, artificial intelligence and nature-inspired computation. He is the author of more than 50 refereed journal and conference papers and co-editor of The Art of Artificial Evolution. He is member of the editorial board of the Journal of Mathematics and the Arts and of the Genetic Programming and Evolvable Machines Journal. He is also the recipient of several scientific awards, including the award for Excellence and Merit in Artificial Intelligence granted by the Portuguese Association for Artificial Intelligence. Recently, his work been featured in Wired U.K. and included in a special exhibition at the Museum of Modern Art (MoMA), New York.

SOMA (SELF-ORGANIZING MAP ANTS)

SOMA is a software model of a dynamic system in which a virtual population of ant-like drawing agents develops individual behaviors in response to marks on a surface that they collectively modify. A small neural network called a Kohonen self-organizing map (SOM), which responds to nearby patterns on the drawing surface, regulates the motion of each ant. The SOM determines the ant's next move and is modified by the most recent pattern in the process. Each ant leaves a trail, contributing to the overall image. When thousands of ants interact this way, a complex multi-directional feedback system in which agents indirectly influence one another's internal structures forms through the effects the ants have on their surroundings. It is difficult to predict what will happen without running the system.

The images reproduced here were taken from separate runs, with different starting configurations, numbers of ants, trail persistence, sensor configurations, movement capabilities, individual trail colors and color responses. I had a bias in seeking to find combinations of parameters that would lead to clear yet constantly changing visual structures, while avoiding sequences that either dissolved to gray or seemed to get stuck in a rut. The runs are intended to be viewed "live" during the process of development, without a set time limit.

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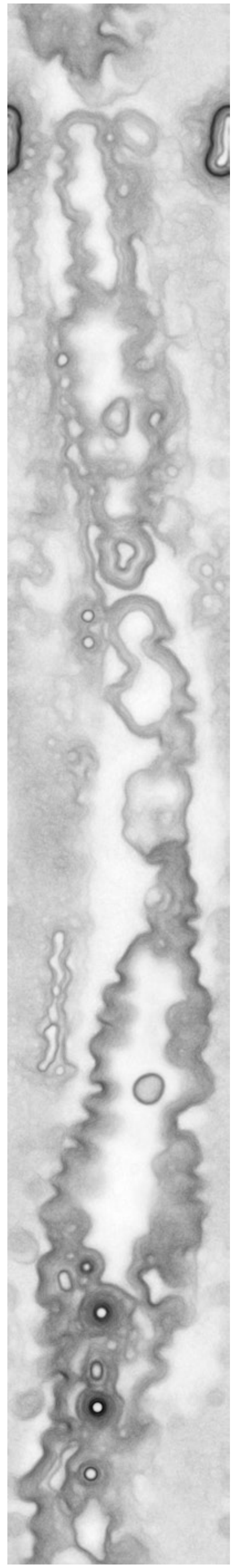
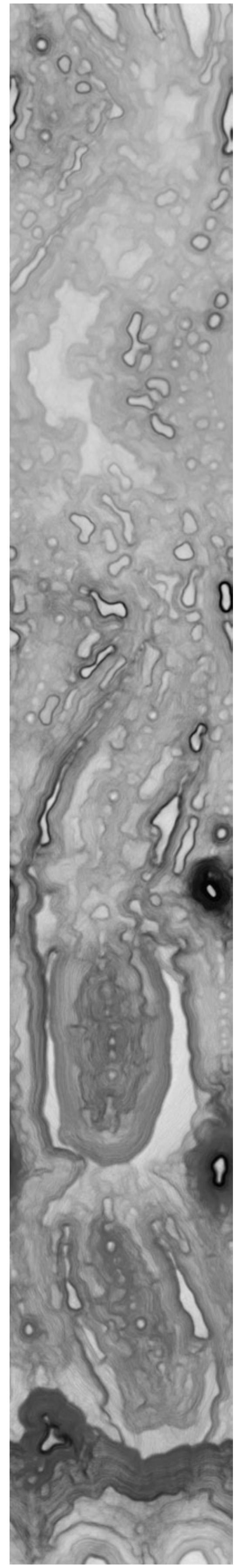
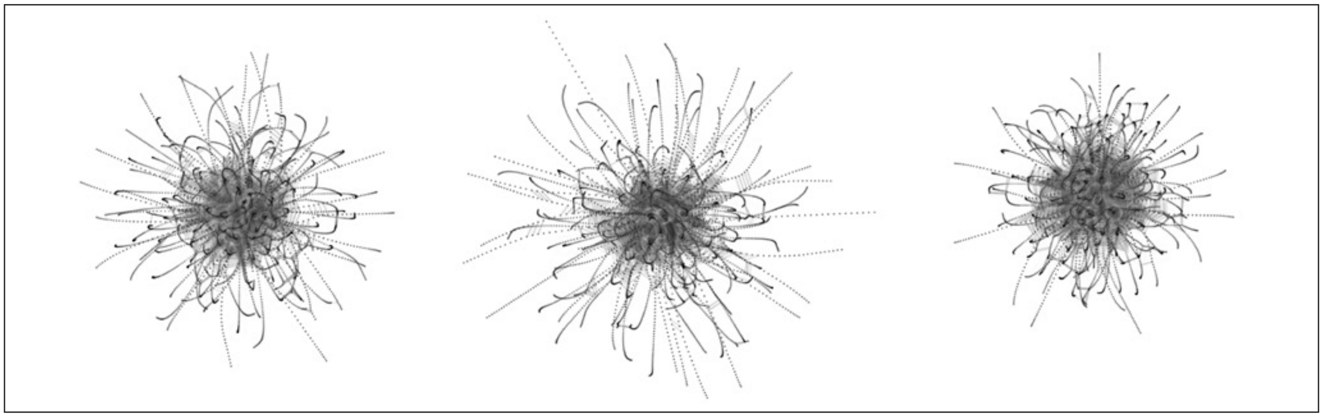


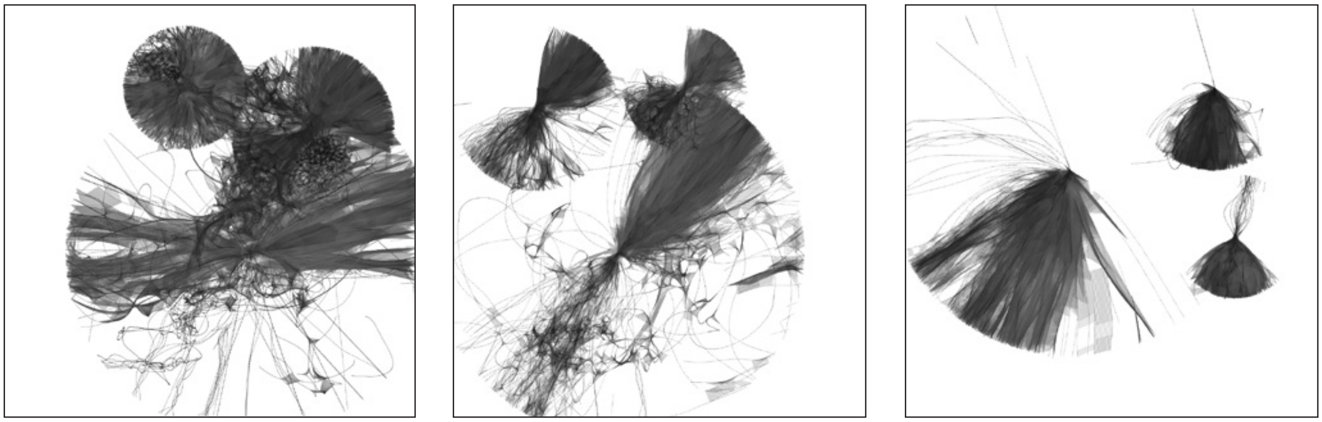
***Soma 416 frame 159*, screen image from volatile sequence, 4200 × 600 pixels, 2005. (© Tim Barrass)**



***Soma 435 frame 026*, screen image from volatile sequence, 4200 × 600 pixels, 2005. (© Tim Barrass)**



***Small Blue Triple*, 3000 × 900 pixels, still from digital animation, 2009. (© Alice Eldridge)**



***Pobpom* with variable size preferences (max, mid, min), 1000 × 1000 pixels, still from digital animation, 2009. (© Alice Eldridge)**

You Pretty Little Flocker

Even when we know exactly what is going on in formal terms, the dynamics of many models of collective behavior are compelling: The emergent behavior is often uncannily lifelike and belies its origin in simple self-organizing mechanisms. A basic bio-logic shines through, even in static representations. Such models constitute a rich compendium for the generative arts. But how do we go beyond simply visualizing scientific simulations and manipulate these models for use in design and creative art contexts?

When we play with these models, it becomes apparent that the emergent dynamics occupy only a fraction of the entire potential state-space of the system. *You Pretty Little Flocker* began as a technical study exploring issues of control, manipulation and representation in algorithmic arts: How might we expand the space of possibilities? How might we steer the system through these models without sabotaging the core self-organizing processes? Is the generative potential or aesthetic appeal of these systems inherent in the model or tied to particular rendering methods?

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Ant Paintings

I first became aware of ant paintings when Nicolas Monmarché spoke about them at the 2003 Congress on Evolutionary Computation (CEC) Conference. My first project used non-interactive artificial evolution to evolve ant paintings where two castes of ants explored and exploited their environment based on color cues.

One of the most fascinating things about ants is their use of pheromones. My second project also used non-interactive evolution to evolve ant paintings, but this time two colonies competed for territory by chemically sensing food in the environment while also using pheromones they deposited to help control following and avoidance behaviors.

The variety of behaviors exhibited by different species of ants is astounding. Stanford biologist Deborah Gordon studies the seed-harvesting ant species *P. barbatus*. Foragers of this species stream out along well-established trails before scattering to find seeds, which they return to the nest using the shortest route possible. My most recent project stylizes this behavior by having virtual ants of this species stream out along uniformly spaced trails.

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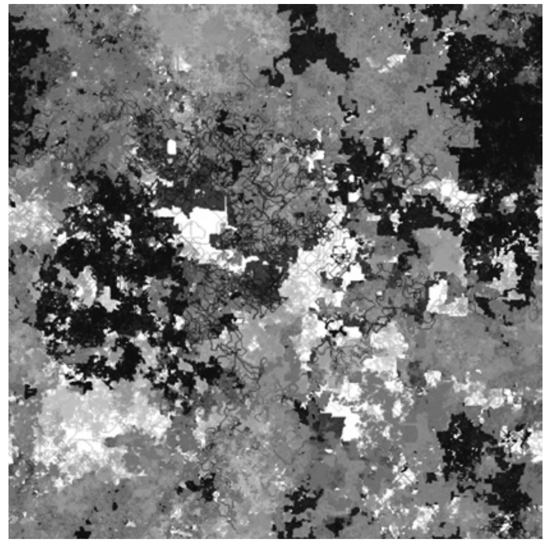
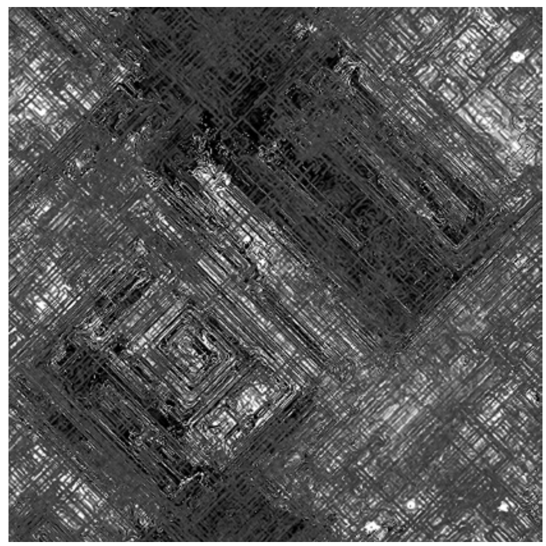
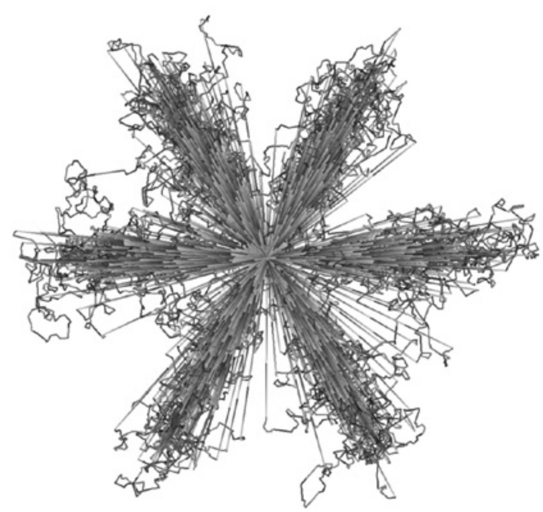


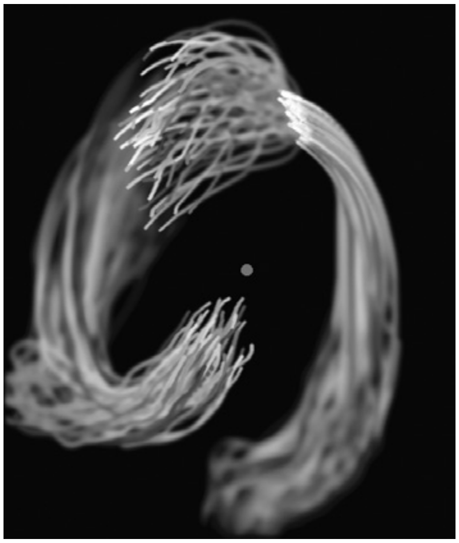
***Ant Painting #21529*, 6 × 6 inches, digital print, 2004. (© Gary Greenfield)**



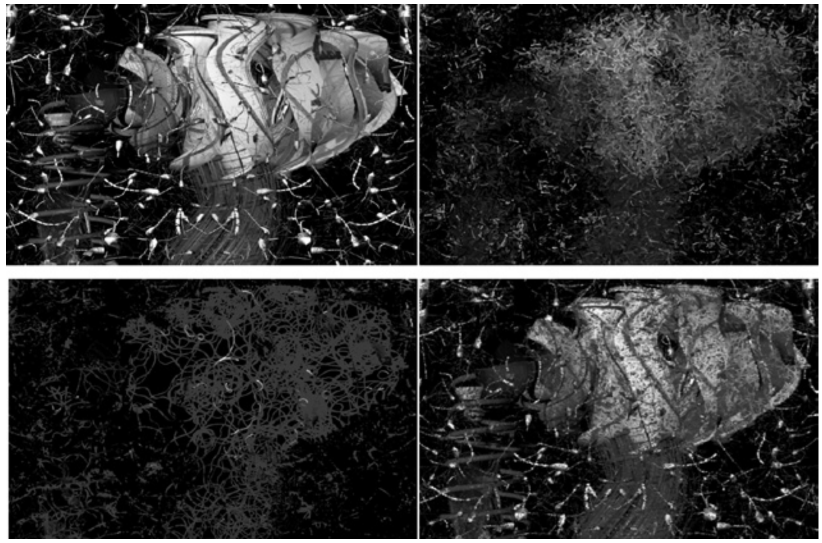
***Ant Painting #22360*, 6 × 6 inches, digital print, 2006. (© Gary Greenfield)**



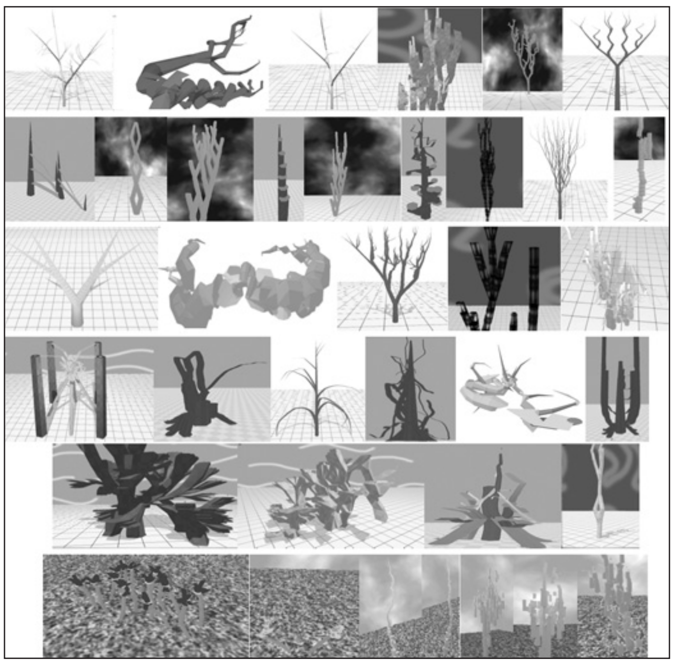
***Ant Painting #6697*, 10.5 × 10.5 inches, digital print, 2012. (© Gary Greenfield)**



SwarmArt 2003, digital image, 623 × 737 pixels, 2003. (© Christian Jacob and Gerald Hushlak)



Sculpture Painting Swarm Redraw, digital image, 1462 × 962 pixels, 2004. (© Christian Jacob and Gerald Hushlak)



Swarm Grammar Art, digital image, 1039 × 1018 pixels, 2008. (© Christian Jacob and Sebastian von Mammen)

SwarmArt

I am interested in swarm intelligence. How can large numbers of individual entities form a seemingly organized "super organism"? I look at schools of fish, flocks of birds, ant colonies and termites and I wonder how their higher-level structures emerge without any central control. Can the world be described by programs or by simple sets of rules that describe singular behaviors? If large numbers of entities following these rules then interact with each other, what do we get? Under which circumstances do we get "interesting" patterns—through organization, structure or orchestrated behaviors? Is this how we can build the next generation of computing devices? Is this a new way to create art? Is this a new way to build virtual organisms?

The works described here were executed in collaboration with Gerald Hushlak and Sebastian von Mammen. *SwarmArt 2003* is swarm art on a 2D canvas. Swarm agents follow a cursor (marked by a red dot). This dot acts as a painting device. As they move, the swarms leave traces behind, which—over time—evaporate and blend into the background.

For *Sculpture Painting Swarm Redraw*, Gerald Hushlak and I experimented with 3D forms and created virtual sculptures. We took virtual photographs of the sculptures and projected these photos onto a virtual 2D canvas. Swarm agents would interact with the projections on the canvas, picking up cues (colors) and interpreting these as commands for the agents. Most agents take a color and "run with it." As an increasing number of agents work on the canvas, more and more of the actual painting is revealed.

Swarm Grammar Art is a collage of 3D structures generated by swarm grammars. Swarm agents are controlled by rules that are formulated as grammars (extensions of Lindenmayer systems). Agents interact with one another through repulsion and attraction and leave behind traces in the form of 3D objects. Some of these structures were bred through our own interactive evolutionary software.

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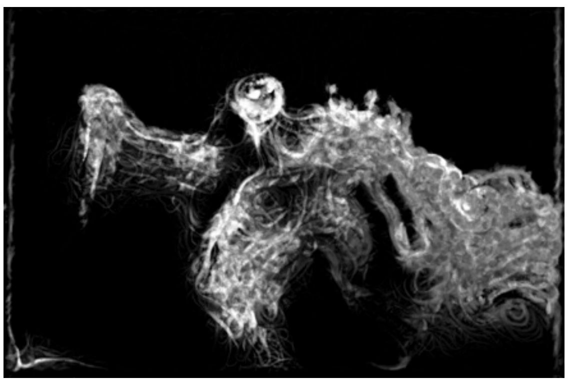
***Nude* #7, 50 × 50 cm, inkjet print on photo rag bright white paper, 2011. (© Penousal Machado)**



***Nude #13B*, 75 × 50 cm, inkjet print on Photo Rag Bright White paper, 2013. (© Penousal Machado)**

***Breakfast*, 50 × 75 cm, inkjet print on photo rag bright white paper, 2011. (© Penousal Machado)**

PHOTOGROWTH

Photogrowth is a software system that uses the exploration of rich organic lines as an ornamentation technique. The algorithm is inspired by ant colonies: It uses artificial ants with different life spans, sensory capabilities and behaviors to produce a non-photorealistic rendering of an image. Each superimposed line represents the continuous trail of an artificial ant. The intertwinement of trails, together with their variation in width and direction, produces richly detailed and expressive artworks from an original underlying photograph (or digital image).

The painting algorithm generates scalable vector graphics that provide resolution-independent images. Experimentation revealed that tuning the parameters by hand did not allow for full exploration of the system's capabilities, hindering its creative potential. Therefore, my group developed an interactive genetic algorithm to evolve the behaviors of species of ants based on these parameters, allowing artists to guide the algorithm according to their preferences without the need to understand its intricacies. *Nude #7* and *Breakfast* evolved using this approach.

The most recent improvement to Photogrowth automates the exploration of parameter space and thus eliminates the need for low-level modification of parameters and image assessment by the user. *Nude #13B* was created using a fitness function that emphasizes change of trail direction, coverage of the canvas and adherence to the original image. With this program, artists are designers of fitness functions guiding evolution. Ideally this will lead to results consistent with their artistic intentions.

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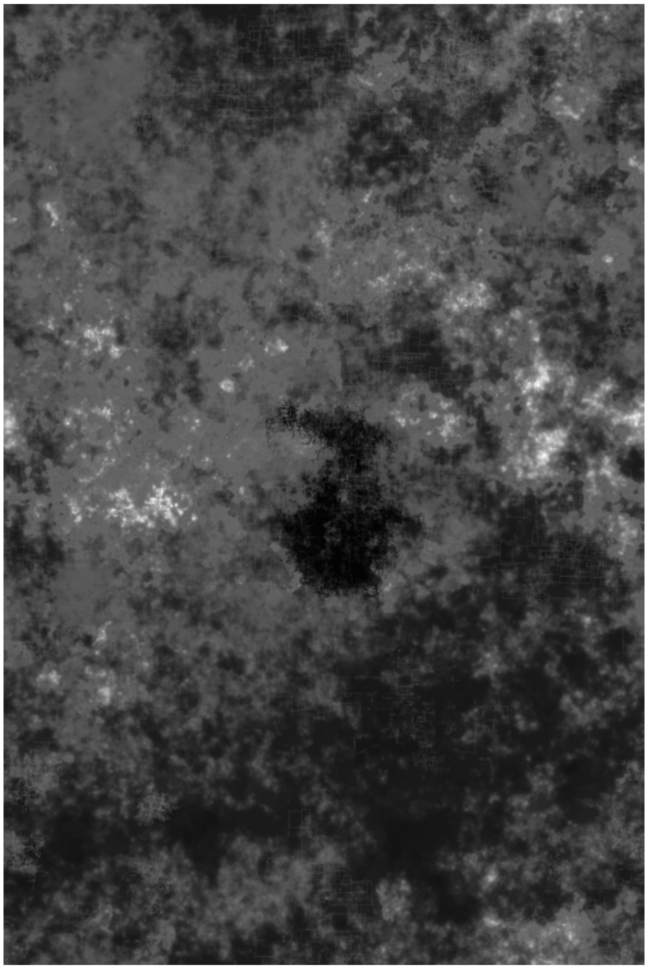

AP20121129B, digital image, 3072 × 4608 pixels, 2012. (© Nicolas Monmarché)

AP20110720Eb, digital image, 1317 × 2048 pixels, 2011. (© Nicolas Monmarché)

Virtual Ant Paintings

When I first began creating ant paintings, my goal was to try to popularize ant algorithms by explaining to a wider audience how we simulate ants with a computer. I decided to draw ant trajectories on screen by marking their paths with colors in a manner that revealed how they used pheromones. To my surprise, this simple artificial life experiment quickly produced an aesthetic effect. Subsequently, I discovered how to define virtual ants by movement and color preferences in such a way that an immense search space (i.e. a potentially immense number of images) was available for exploration using interactive evolutionary algorithms.

Ant painting AP20121129B shows 16 ants interacting for 50,000,000 time steps and took 2071 seconds to render. It highlights "blue" and "red" ants competing for territory, with the red ant minority dominating due to the self-following behavior of the blue ant majority.

Ant painting AP20110720Eb uses only 6 ants and lasts 10,000,000 time steps. It was created by allowing the ants to respond to a static landscape of pheromones furnished by an image of the *Mona Lisa*. The colors deposited by the ants are thus the same as those in the *Mona Lisa*. Given sufficient time and patience, these 6 ants were able to "statistically" reconstruct the *Mona Lisa*.

I find it significant that this experimental generative art project has also led to further theoretical research concerning the complexity and the prediction of behavioral interactions, the development of an introductory programming project and potential applications in design.

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NON-PHOTOREALISTIC RENDERING WITH INTERACTIVE, AGENT-BASED COMPUTATION

Our intent is to alter the "realism" of an original image by iteratively modifying very tiny portions of it. Our swarm algorithm does not comprehend the image's objects, subject or evocative purpose. Instead, its virtual agents each regard the image as a pixel-level environment of spatially gridded cells. Each cell has a digital luminance. The artificial agents traverse the environment along pathways indicated by the luminance gradients among adjoining cells, focusing on areas of importance using jumps, edges and threshold levels for decisions. They modify a cell's state according to simple rules that consult their path history and drawing parameters. From their collective, locally interacting behaviors emerge two styles that, to an external observer, are interpretable as a painterly rendering or pencil sketching. Our system of agent-bit-level computation—under artist control and over the digital canvas—is an active and emergent mediation of creativity and automation.

Dancer #1 and *Dancer #2* show two different painterly renderings of an original photograph using our system.

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UNA-MAY O'REILLY
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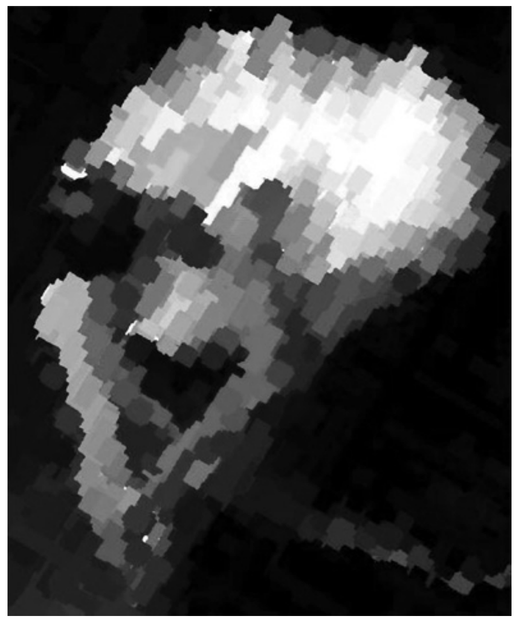
Dancer **(photographer unknown).**

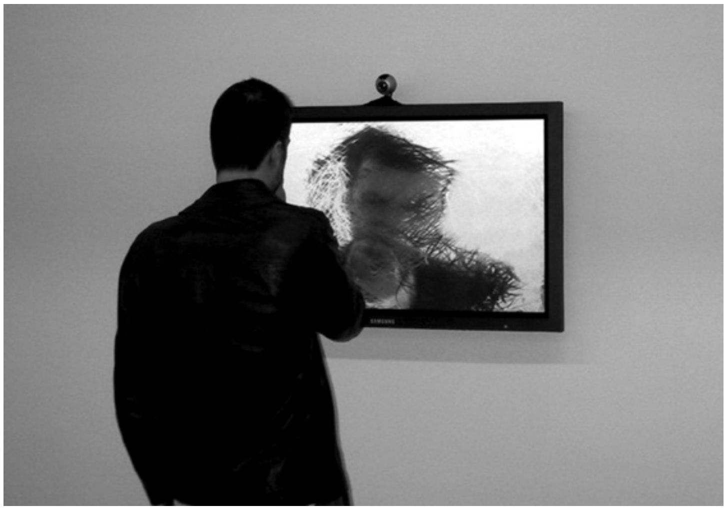


Dancer #1**, 1000 × 1210 pixels, digital image, 2004. (© Yann Semet, Fredo Durand and Una-May O'Reilly)**

Dancer #2**, 1000 × 1210 pixels, digital image, 2004. (© Yann Semet, Fredo Durand and Una-May O'Reilly)**

Swarm #1, **screenshot from live video installation, 2002. (© Daniel Shiffman)**

Swarm #2, **screenshot from live video installation, 2002. (© Daniel Shiffman)**



Swarm #3, **photo from live video installation, Savannah College of Art and Design, 2004. (© Daniel Shiffman)**

SWARM

Swarm is an interactive video installation that implements an algorithm model to create patterns of virtual flocking birds based on Craig Reynolds's Boids model as constantly moving brush strokes. Taking inspiration from Jackson Pollock's drip-and-splash technique of pouring a continuous stream of paint onto a canvas, *Swarm* creates smears of colors captured from live video input, producing an organic painterly effect in real time.

A flock of birds, swarm of bees or school of fish all exhibit intriguing and beautiful group behaviors. These systems may appear to be centralized, with members of the group following one leader. Rather they come to life via each individual following simple rules for local interaction. Craig Reynolds's system is a model for implementing these rules computationally for computer animation.

Swarm is implemented as a system of 120 boids following the rules outlined by Reynolds. In my system, each boid looks up an RGB color from its corresponding pixel location in the live video stream. If the viewer stands still, his or her image will be slowly revealed over time as the flock makes its way around the entire screen. If the viewer chooses to move during the painting process, more abstract shapes and colors can be generated.

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T. albipennis Sand Artists

My *T. albipennis* sand painting virtual artists draw direct inspiration from the ant species *Temnothorax albipennis*. Colonies of this species of ant build simple circular walls composed of grains of sand or fragments of stones at a given distance from the central cluster of adult ants and brood. The cluster functions as a template that, when combined with self-organization, is responsible for the particular wall pattern formation. My *T. albipennis* artists are artificial 2D builders. Starting from an unorganized placement of virtual sand grains, the ants rearrange the grains, creating patterns composed of scattered pointillistic and imperfect circles: a colored moon-like landscape full of craters. I use different colonies (each with a specific radius, color, nest center and wall thickness). Individual ants pick up and drop grains with the color of their respective colony. The probability of dropping and picking up is strongly dependent on the species's nest template. The ants compete for grains and for space whenever multiple colonies with the same color or nest boundaries overlap.

T. albi #1 and *T. albi #2* both used canvases that were 74% occupied by randomly scattered grains of three different three colors. *T. albi #1* used 2000 ants divided into 99 colonies, and nest radii never exceeded 600 pixels. *T. albi #2* used 989 ants divided into 99 colonies, and nest radii never exceeded 100. For *T. albi #3,* the grain coverage was reduced to 59% of the canvas, but it had 10 colors of sand grains and used 10750 ants divided in 500 colonies whose nest radii never exceed 100.

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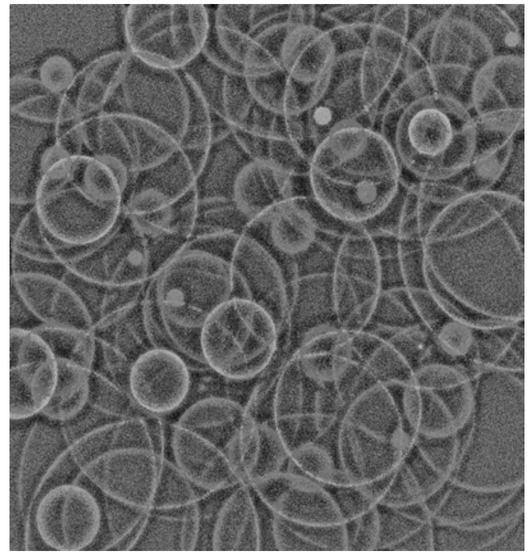

***T. albi #1*, 7 × 7 inches, digital image, 2013.**
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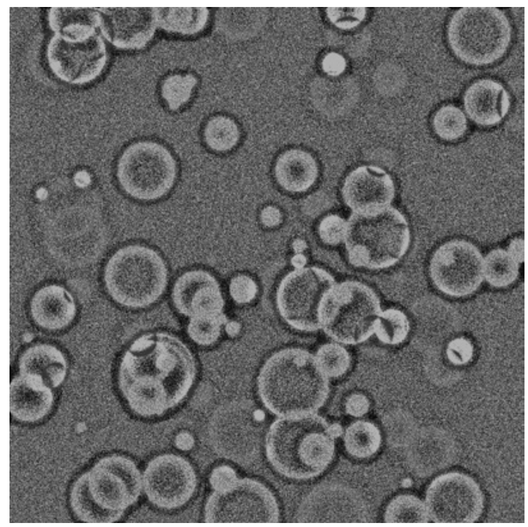

***T. albi #2*, 7 × 7 inches, digital image, 2013.**
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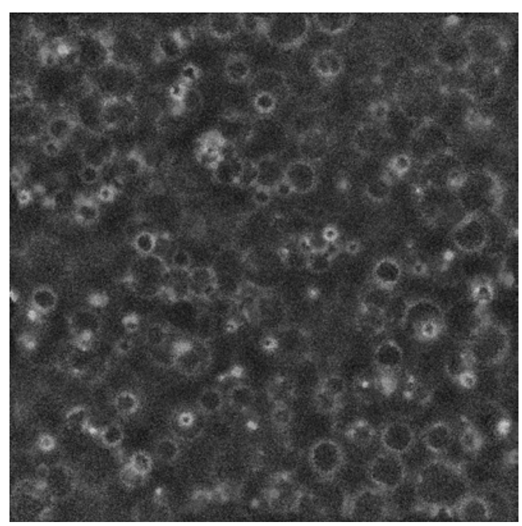

***T. albi #3*, 7 × 7 inches, digital image, 2013.**
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