Computational Evolutionary Art: Artificial Life and Effective Complexity

Tiago Barros Pontes e Silva(✉)

Brasília University, Brasília, Brazil
tiagobarros@unb.br

Abstract. On the field of Evolutionary Computational Art, artists frequently adopt a top-down process of creation, employing the algorithms only as a mean to express a previously conceived composition. In this sense, the present paper aims to discuss the use of Genetic Algorithms for the development of systems with greater level of emergence, running towards the increase of its effective complexity, understood as suggested by Gell-Mann. In this context it is presented the system Morphogenesis. It was developed as a Multi-Agent Adaptive System, built with Genetic Algorithms to generate movement, feeding, fighting and reproductive behaviors. All these behaviors are programed at the individual level, from which emerge the macro patterns of the groups, simulating the evolutionary process. The system analysis suggests that the fitness function should not be focused at the arrangements of the agents' genotype, but at the adaptation of the phenotype itself. It is expected that the use of algorithms that allow expressions closer to the evolutionary process has a greater affinity with the aesthetic notion proposed for the field of Evolutionary Computational Art. Hereupon, a qualitative exploratory study was conducted to compare the perception of the high effective complexity arrangements against random arrangements. Preliminary results show that the evolutionary process could be associated with a greater evaluation of intentionality of the compositions and could be also related with a deeper aesthetic evaluation.

Keywords: Computational Art · Artificial Life · Effective complexity

1 Introduction

Nowadays the current technology allows a variety of experimentation on the field of Computational Art. Notwithstanding the advances of the creations since its first artists like Herbert Franke, Michael Noll, Frieder Nake, Manfred Mohr or Edward Zadec, the contemporary artists and researchers are questioning their object of study and the way the poetics have been conceived. Today, the simple adoption of the computational process does not add value to the proposed works. Artists are asked how to be faithful to the chosen artifacts and materials, showing the intrinsic characteristics to the computational processes [1].

More specifically at the field of Evolutionary and Generative Art, Galanter [2, 3] presents some tangible challenges to the artists. The first one is the absence of an automatic Aesthetic Fitness Function to evolve the systems. The lack of knowledge

A. Marcus and W. Wang (Eds.): HCII 2019, LNCS 11584, pp. 331–346, 2019.
https://doi.org/10.1007/978-3-030-23541-3_24

about the human aesthetic judgement is considered an obstacle for an automated function. The human judgement is susceptible to fatigue, making the evaluation less consistent over time [4]. Besides, when this subjective judgement is directly attributed to the public by an interactive system, the processing capacity of the system is reduced, generating a limiter [5].

Moreover, another problem pointed by Galanter [3, 6] is the difference between the level of complexity existing in nature and on its genetic representation when compared to the computational systems created by artists. In this scenario, the concept of complexity is not considered simply as the amount of information of the visual representations, but a combination of organization and chaos in order to promote contextual effectiveness. Therefore, it is considered as the Effective Complexity presented by Gell-Mann [7], comprehended as the measure of the most compressed description of the regularities of a communication process or an algorithm. Nonetheless, the regularities can only be defined according to its relevance to a specific context.

The current study aims to present the Artificial Life system entitled Morphogenesis as an early answer to these questions. To seek for a greater level of emergence on its compositions, the evolutionary process will be simulated to achieve an increase on its Effective Complexity. The study begins from the premise that Effective Complexity is similar to the Organized Complexity proposed by Dawkins [8]. According to the author, the organized complexity is more than just heterogeneity. It consists of a specific type of heterogeneity that is slowly selected by nature due to a proficiency or is entirely conceived by a human top-down process to have a functionality.

2 The Features of the System Morphogenesis

2.1 Intended Aesthetics

The intended aesthetic for the system Morphogenesis is related to the composition of microscopic images. It is inspired by the first experiments of computational art, using geometric shapes as the representation of its agents. Although built as a composition of geometric agents, the system must also imply the organic feeling of a living system through its behavior. Thereby, its poetic approaches the emerging patterns of the living systems applied to the metaphoric world of microscopic images. It works as if it was possible to watch the very cells of every picture fighting to impose its shapes, colors and sounds. In other words, it is suggested to the public the experience of observing the fundamentals of visual and sound language interacting while transformed by the evolutionary process.

The main influences of the system were the Dawkins' Biomorphs [8] and the Conway's Game of Life [9]. The intention is to create a system that can navigate through the genetic space of its creatures like in Biomorphs, but with automatic rules of proximity, similar to the Game of Life. For more information about the intended levels of significance and the emergent discussions, see [10].

2.2 Development Process

The system development was considered a creative heuristic process of experimentation. The bottom-up approach was necessary to balance the agents' interactions so that life becomes probable in every performance. To achieve a self-organized arrangement a Multi-agent Complex Adaptive System [11] with Evolutionary Algorithms was built, using Genetic Algorithms [11, 12] and Swarm Intelligence [13]. The entire system was conceived using Processing 2.0.

The name Morphogenesis was chosen to represent the origin of microscopic compositions, meaning the origin of shapes. Also, it is a tribute to Alan Turing, who also wrote The Chemical Basis of Morphogenesis [14] discussing the emergence of complex structures from simple patterns. To understand the system's behavior and the meaning of the compositions, it is necessary first to comprehend its laws of creation presented below.

2.3 The Agent's Representation

Each agent has a body composed by a line that crosses 4 to 7 points randomly generated inside a square with a side between 25 and 100 pixels. It is a Catmull-Rom spline calculated to simulate a handwrite line with an assorted weight, also randomly specified. Sometimes the internal points can receive the line twice to create a loop. With this set of parameters, it is possible to simulate a scratch (Fig. 1).

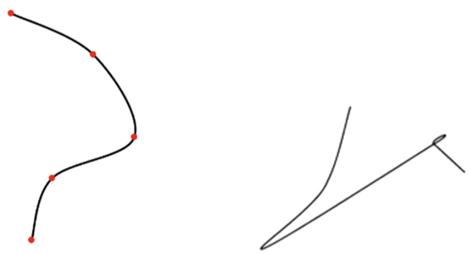

Fig. 1. Two examples of the line that constitutes the agent's body. The first (left) highlights the points used to calculate the spline. The second (right) illustrates the loop of the line.

After the definition of the body's structure, three geometric shapes are inserted on the first, the second and last point. The shapes can either be a circle, a triangle or a pentagon. The first one defines the type of the agent and is also the larger shape of the body. When the agents interact to each other, shapes with a difference of sides bigger than 2 will be considered enemies, whilst agents with the same shape, or with a difference of only 1 side, will be considered friends (Fig. 2).

The agents also have 2 colors, one for the line and other for the fill, received as an RGB value. All these features are stored in the agent's DNA, retrieved later for its reproduction. With these features, it is possible to give the agent some visual identity, making it different from the others (Fig. 3).

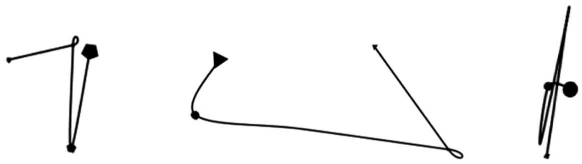

Fig. 2. Different types of agents defined by the larger shape of the body. From left to right, the pentagon, triangle and circle shape.

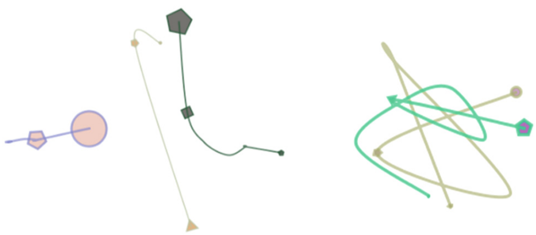

Fig. 3. Agents with its colors, one for the line and other for the fill. All the agent's information is stored in its DNA and helps to give the agent a visual identity. (Color figure online)

Also, it is possible to simulate a scrawl surface with several agents conceived with random attributes (Fig. 4). As expected, there is a homogeneous distribution of the information in this situation, implying a low effective complexity state derived from its randomness.

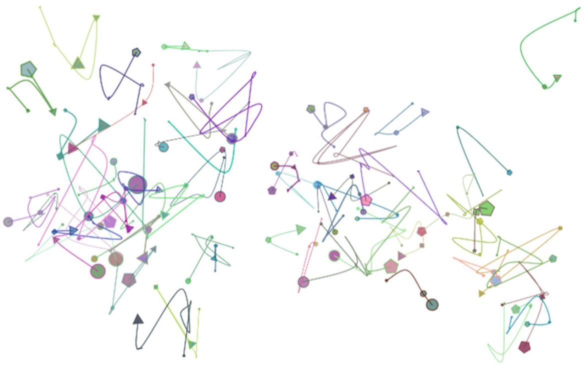

Fig. 4. Composition with 60 randomly generated agents. The variation of the agents' DNA determines the random distribution of the composition.

The agents also have a sound of their own. They are capable to reproduce a musical note from a specific instrument of the Java Sound API. Along the visual stimuli, the overlap of agents' sounds creates a symphony of random noise at the runtime's firsts stages.

There is also the representation of dead agents, where they lose their movement, colors and sounds. In this circumstance, the agent is represented in gray, always losing opacity and sound volume until completely vanished from the screen (Fig. 5).

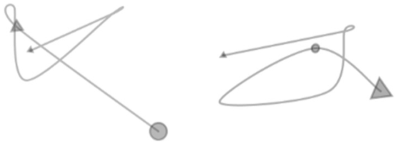

Fig. 5. Two dead agents vanishing from the screen.

2.4 The Agents' Drift

As a system inspired by Conway´s Game of Life [9], the main variable to define the behavior of the agent is its position in relation to the others. Every agent has a basic random movement, a reference to the Brownian motion [15]. What determines the displacement of the agent is the resultant of all the other variables that interfere with the random probability. As an example, when an agent is influenced by another and tries to move away, the random probability of the original Brownian movement is weighted, altering the chances on each frame.

This feature prevents the agents from being perceived as bots flying on the screen. Instead, they move with an organic uncertainty that reminds the microscopic lives. When the head moves, all the other points of the body move along with an easing effect, simulating an organic elastic matter (Fig. 6).

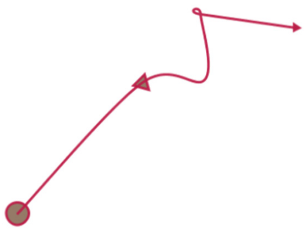

Fig. 6. Example of the easing effect that delays the movement of the points of the agent's body. With this effect the body tends to stretch during the motion and to accommodate when it stops.

2.5 The Environment

Despite the positions of the other agents, the two-dimensional space where they live has no influence on their behavior. Besides that, it is possible to choose a color to the background to improve the visual composition of the arrangement. The main choice is an automatic color calculated as the average fill colors of all agents. This allows the expression of particular compositions (Fig. 7).

Fig. 7. Background color calculated as average fill color of all agents. (Color figure online)

2.6 Endogenous Interactions

The displacement behavior of the agents can be affected by the presence of other agents in several situations:

- a weaker foe to be chased;
- a stronger foe to flee from;
- a pair for mating;
- a friend for protection;
- a corpse of a dead friend to avoid;
- a dead foe that could serve as food.

In these cases, the collision detection occurs only on the head of the agents. There are three stages of detection based on its size: (a) the agents can't see each other, when the distance of the center of the heads is bigger than eight times the sum of the heads' radius; (b) the agents see each other, when this distance is smaller than that, but the agents are not yet colliding; (c) the agents' heads collide.

On the first stage, the agent´s movement is not influenced by another presence. When the agents can see each other, they can try to come closer or to move away, depending on the evaluation made of the status of the other agent (alive or dead), its strength, its type based on the head's shape (friend or foe) or if its ovulating and ready to mate. When the agents' heads touch each other, they can fight, reproduce, eat or do nothing at all (Fig. 8).

Also, there is a special situation when the agent's head crosses another point of the body of the other agents. In this circumstance, if the second shape of the body of that agent is the same of the agent's head, it can be trapped. While trapped, it becomes a limp of the other agent, having its life being drained. This effect happens regardless of whether they are friends or enemies (Fig. 9). Finally, there is one last possible interaction. When the agents consider themselves friends, the last shape of the body is checked. When it is the same, they can group to act like flocks, increasing the chances of staying close to each other (Fig. 9).

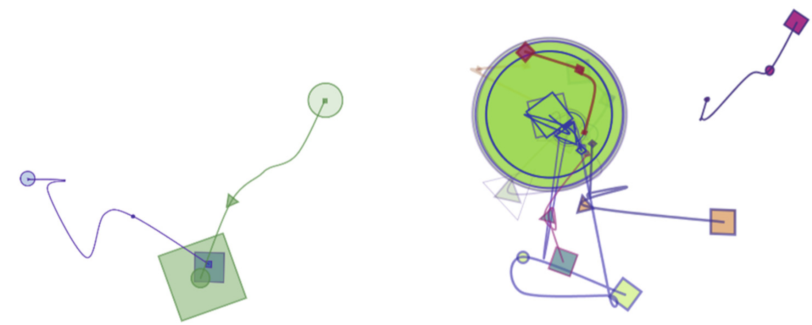

Fig. 8. Examples of two collision situations. The first on the left is a fight between agents, identified by a flashing square on their heads. The second on the right is a mating, identified by a circle flashing on their heads.

Fig. 9. Two examples of different interactions between agents. On the left there is a triangle agent trapped on the body of a circle agent. On the right there is a friendly group of square agents.

2.7 The Reproductive Process

After two agents ovulate, find each other and are capable of reaching their heads to a collision, the reproductive process begins. Once they can spend some time together mating, as illustrated previously, a new life is born.

Although, differently from the first generation created randomly by the system, this new life has a recombined DNA from its parents. Like other living species, the agents are constituted by a pair of variables for each feature. When they reproduce, a new recombination is generated for each pair of the agent's DNA. This allows the maintenance of the genetic variability of the system, as suggested by Dawkins [8]. Also, with that property, every agent has its own DNA composition. It can look similar to the other brothers, but not exactly the same. This effect cannot be achieved if the new DNA is composed by the mean of the parents' DNA, what would lead to a loss of genetic variability on the system (Fig. 10).

The agents' DNA is composed by 66 variables that define their color, sound, speed, amount of life, size, shape, maturity, among other properties. Also, when the reproduction occurs, there is 1% chance of mutation that can happen to each recombination, increasing or decreasing a bit the value of that feature. The mutation is another important

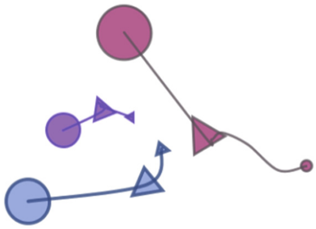

Fig. 10. A new life born near the parents with a recombined DNA.

feature for the evolutionary process. In a short-term, the persistence of the DNA is relevant for the success of the new life. However, in a long-term, mutation is necessary to shape flexible structures, making life probable on adaptable environments [8].

This effect can happen even on the shape of the head that determines the type of the agent. If this happens, the number of sides of the geometrical shape can change. If it still has a difference of only 1 side, it will be considered friend. But if the mutation continues and the difference becomes bigger than 2 sides, it will be considered an enemy. This feature is significant because it allows the navigation trough the genetic space of the agents, creating new species of geometric agents shaped by the evolutionary process, as purposed by the system Biomorphs [8].

2.8 Genetic Algorithm and Fitness Function

Nevertheless, the selection process of the most adapted agents from the system Morphogenesis differs from the Biomorphs. Due to the consistency problems of the human judgement guiding the evolutionary process [4], an automated selection was programmed. Yet, the use of the Genetic Algorithm was not directed to the ideal set of the agents' DNA as a declared Fitness Function [16]. Inspired by natural life, the selection is not calculated by a direct formal equation. Instead, all agents have an amount of life that is lost with time. The agents that are capable to live long enough and reproduce can transmit their DNA. Hence, the best properties for the agents' life are not programmed in a top-down approach. They emerge from the agents' interactions. Consequently, the properties are not selected by their genotype, but for their phenotype. The best DNA set cannot be identified at first.

The decisions taken by the agents are programmed by a state machine that relates its inputs and outcomes. The only possible outcome is a weight on the random displacement probability. With the DNA recombination and the mutation process, the agents can evolve to a complete distinct set of behaviors from the first programmed generation. If somehow a new configuration for the conditional hierarchy is established, either for proficiency or chance, it re-interprets the behavior categories presented earlier.

There are several meta-heuristics designed to optimize the search for a solution in a state space [17, 18]. Also, there are Novelty Search Algorithms [19, 20] designed to dynamically find new solutions related to previous findings. In this situation, the genetic algorithm is not used as an approximation function from a previously intendent configuration, nor considers the novelty level of previous findings. It considers the serendipity of life, it is flexible and can keep continually changing to adapt.

2.9 The Morphogenesis Compositions

When the system is launched, 60 agents are randomly created, 20 from each kind (Fig. 4). As the presented rules are applied, each frame creates a new arrangement, reorganizing the agents position and states. Due to the disorganization of the first generation, several fights occur simultaneously. With time, as the generations pass by, the selected genetic variability of the system start to emerge and dominate the scene.

The agents' colors and sounds cannot be perceived by the agents. They are indirectly selected and transmitted to the new generations. This way, they can be processed by the evolutionary process without guiding it. Therefore, the shapes, colors, sounds and arrangements represent an output of the evolutionary process of the Morphogenesis universe. The composition signifies the genetic variability of the living agents, constantly changing alongside the agents' behaviors (Figs. 11, 12, 13 and 14).

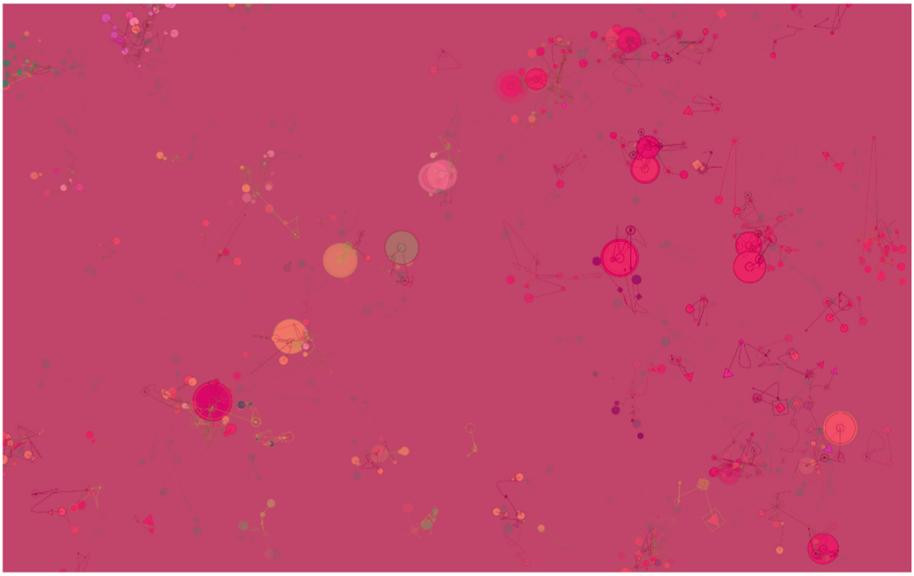

Fig. 11. Composition of a dominant red circle population. The colors represent the genetic variability of the agents. Distant groups have specific colors due to their isolation. (Color figure online)

2.10 Exogenous Interactions

The arrangements presented show the result of the endogenous interactions of the system. The interactions between the public and the system were planned to disrupt this organization as an aesthetic experience. This decision was made because it was difficult

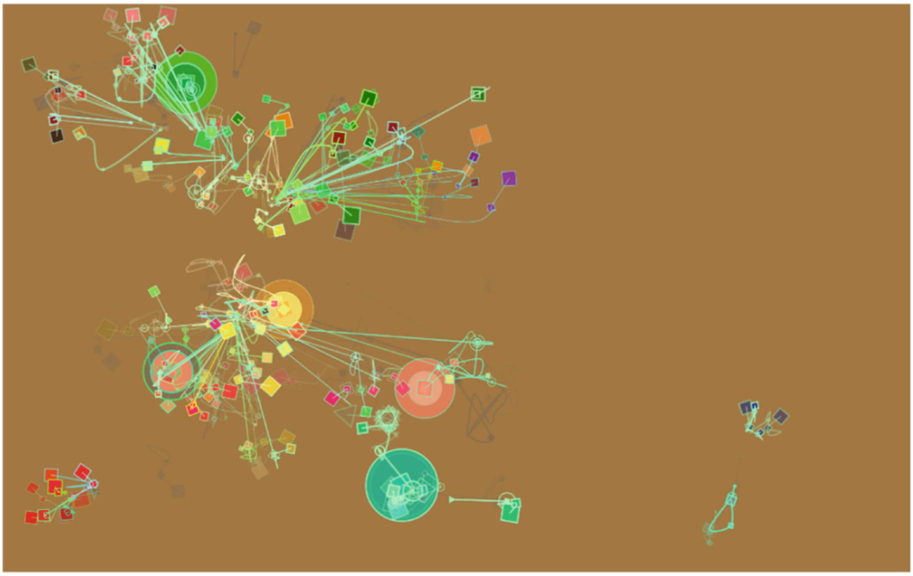

Fig. 12. Composition of a population of squares. This arrangement has a broader genetic variability than the previous one, with more colorful groups. The background becomes a more evident tertiary color. (Color figure online)

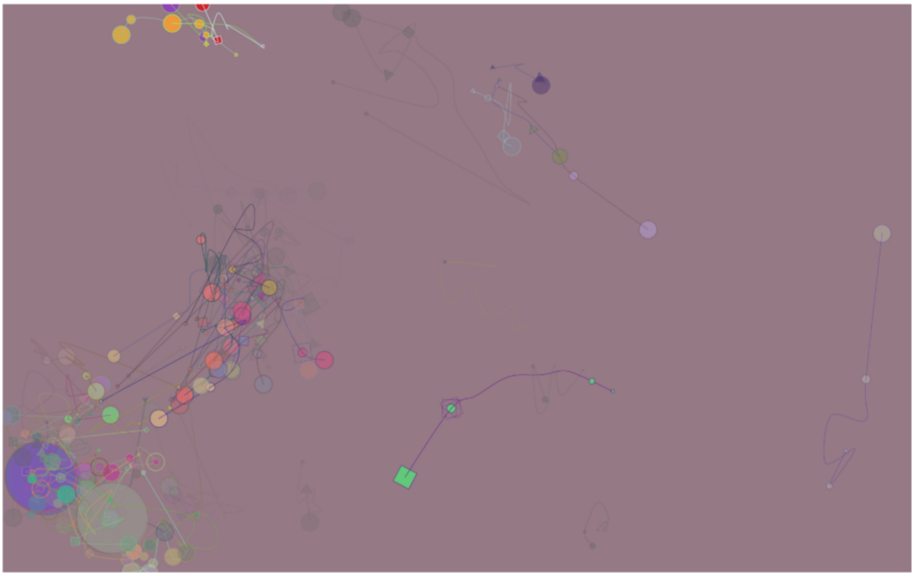

Fig. 13. Composition of a shoal of circles been predated by a stronger square. This is an emergent behavior of the system, since the conduct of the species was specialized by evolution. Circles have a short life and are weaker but succeeded as group, while the square lives alone for a longer time because it can feed from the shoal.

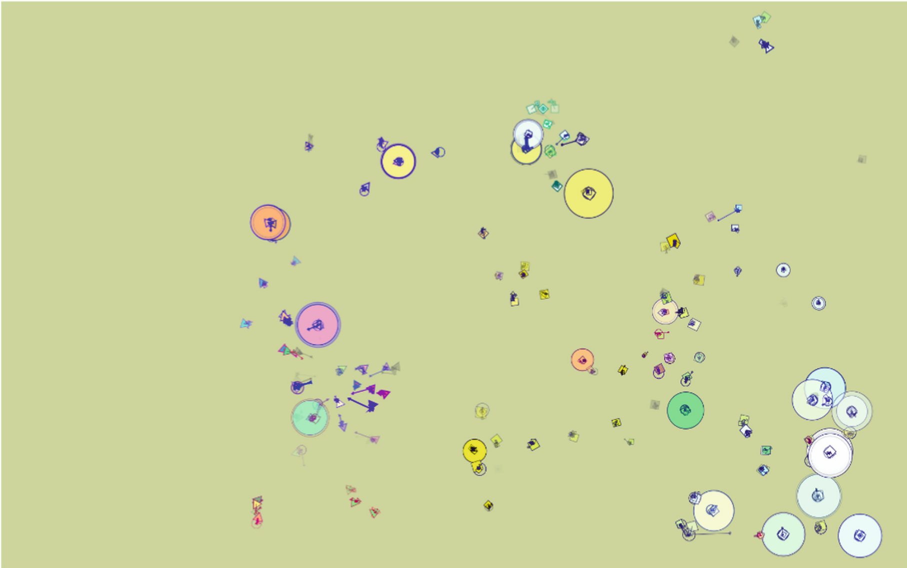

Fig. 14. Composition with a different agents' behavior, illustrating the navigation through the genetic space. This new specie only moves when there is intention of fighting, feeding, or mating with a higher speed than que first generation, specializing the use of the displacement.

to balance the behavior of the public with the evolutionary process of the species. The inconsistency and the timing of human actions tend to not contribute to the achievement of complex self-organized structures [4].

Several assemblies were tested to create means for the public to interfere on the Morphogenesis universe. The main configuration encompasses an interactive board that was used to allow touching the system's surface. The human touch bothers the agents, making they leave. Also, when directly touched, they accelerate to protect themselves. This feature alone was enough to create significant experiences, allowing the destruction of entire colonies with a single touch, leaving the public baffled (Fig. 15).

Other possibilities were tested as well, as a video game controller or cameras to capture the public actions. More information about the exogenous interactions can be found in [21].

3 Randomness and Effective Complexity

3.1 Comparison Between the Different Stages of Evolution

The first moments after launching the system creates a random composition of agents, as previously illustrated (Fig. 4). In this situation, the visual and acoustic information is chaotic, homogeneously distributed as suggested by Galanter [2, 3, 6] supported by the

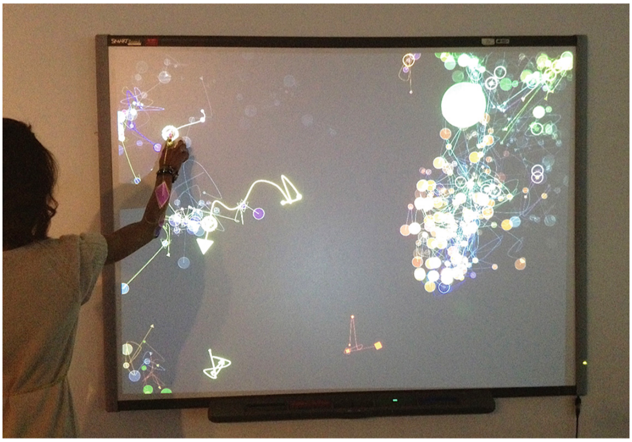

Fig. 15. Main structure used to present the Morphogenesis on exhibitions. An interactive board was used to let the public observe and interact directly with the agents.

statistical law of large numbers [22]. Considering the concept of effective complexity [7], despite the large number of agents, shapes, colors and sounds, the system in this situation is considered with a low amount of complexity. When two compositions randomly created are compared, the difference between them seems irrelevant, like noise (Fig. 16).

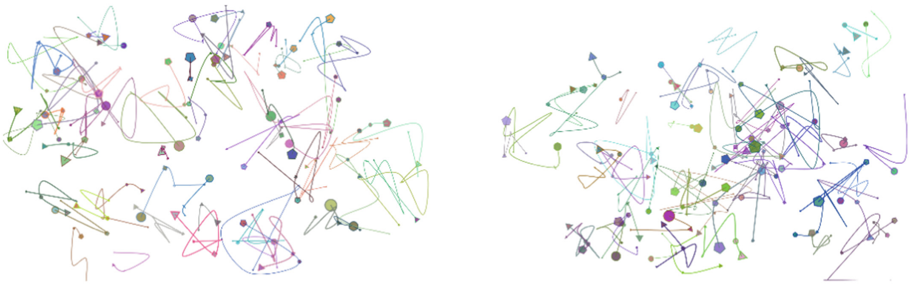

Fig. 16. Comparison between two random compositions. As predicted by Galanter and Gell-Mann, despite the large number of agents, colors and sounds, the arrangements look alike, suggesting a low amount of Effective Complexity. (Color figure online)

Otherwise, when a random composition is compared to another with agents from above 200 generations, the self-organization of the system suggests a pattern that represents the genetic variability of the population shaped by the evolutionary process (Fig. 17).

When interacting with the system in this situation in four art exhibitions performed between 2012 and 2013, the public expressed the feeling of relating with the agents' colonies that could not be completely understood but seemed intentional. This effect

Fig. 17. Comparison between a random composition (left) and a system with agents from above the 200th generation (right). The composition self-organized has a pattern of distribution, color, sound and behavior, suggesting a greater amount of Effective Complexity than the other.

was not recurrent on early stages of development of the system. They frequently asked about the graphic and acoustic compositions of the continuously evolving system.

3.2 The System as an Instrument for an Empirical Study

Due to the public indications, a qualitative preliminary study was conducted to evaluate if the level of intentionality perceived of the arrangements, as well as the aesthetic evaluation of the participants, was related to the Effective Complexity of the composition. The empirical preliminary study is reported in [23].

A set of 30 pictures were created, 15 with random agents and 15 with agents from the 300th generation. Some configurations, as the background color or the number of agents were controlled. Two presentation orders were defined to check if it would influence the evaluation, sorting the group of 30 images in both cases. The participants were requested to answer if the picture was considered attractive and if they think it was made by a person or automatically generated by a computer. Only 10 people participate of the preliminary study to evaluate the instruments and procedures.

The preliminary results suggest that the pictures with a greater Effective Complexity were more attractive to the participants. Almost all of the participants (9 from a total of 10) expressed preference for the high complexity pictures. They expressed more interest on its colors' variations and organization, despite the difficulty to understand the meaning of the composition. It was interpreted as a more organic representation, like when they try to separate noise from a sound of a not known spoken language, suggesting intentionality.

Also, the random pictures were only interpreted as a human creation on the first occurrence. Yet, they were associated with children scrawl, while the complex pictures were perceived as more sophisticated creation. After the arbitrary pattern was recognized, the participants expressed a lack of diversification on the random images, as inferred. This effect started after the second occurrence of a random picture.

3.3 The Perceived Effective Complexity

Gell-Mann [7] defined Effective Complexity pondering its contextual relevance, excluding the noise or redundancy of the communication. However, it is not an easy approach to measure the exact Effective Complexity of some kind of systems. The present study tried to address the issue of aesthetic attractiveness of compositions considering the Effective Complexity as a possible factor. Therefore, reflecting on the Empiric Aesthetic studies of Fechner, Birkhoff [24], Eysenck [25], Berlyne [26] and Martindale [27] discussed by Nadal [28, 29], the relation between order and complexity is not yet well-defined. The recognition of a previously known stimulus is also a strong factor of influence.

Hence, the system Morphogenesis try to emulate an abstract composition with different levels of complexity. To ensure the increase of complexity of the composition without the use of figurative elements, the evolutionary process was applied to shape its visual and acoustic configuration. Consequently, the concept of Organized Complexity [8], comprehended as an output of the evolutionary process or an intentional human creation guided by a proficiency, was associated with the concept of Effective Complexity, understood as a combination of order and chaos with contextual relevance [7].

The self-organized patterns evolved from the system may have been more attractive to the public due to our specialization in recognizing natural outputs that are relevant to our survival, as food or other types of life. Therefore, our own evolutionary process may be responsible for a greater interest in such compositions, in which we are in a search for energy quality to sustain life and drive us apart from entropy, as suggested by Schrödinger [30].

Nonetheless, the role of the system Morphogenesis is to try to answer the questions purposed by Galanter about the superficiality of the current Generative Art approach. Thus, Morphogenesis tries to provide greater level of emergence than a simple algorithmic composition. A possible response learned for future works is the use of evolutionary techniques guided by an adequate proficiency for the creation of compositions with a greater level of Effective Complexity.

Also, it is a first incursion on an evolutionary poetic to provide an aesthetic experience of the evolutionary process. Due to the different manifestation scale, the evolutionary process can be comprehended, but not easily experimented with a panoramic view. The accelerated and simple universe of the Morphogenesis attempts to compress its scale to promote such experience.

4 Conclusion

The study presents the system Morphogenesis as Computer Art, more precisely at the Evolutionary and Generative field. It was conceived to discuss the superficiality of current generative compositions pointed by Galanter. He suggests that these systems should be able to perform more levels of emergence, expressed by the presence of Effective Complexity on the creations. Therefore, it was conceived as a Multi-Agent Complex Adaptive System, representing geometric shapes that should evolve when interacting with each other.

From the exhibitions and a small qualitative preliminary test, it seems that the use of evolutionary techniques was able to trigger the interest of the public in these compositions. Maybe humans tend to have an innate curiosity for this kind of complexity, that symbolize natural complex outputs or for the functioning of our own creations. When interacting with the system, with the necessary disposition to involve themselves with the suggested poetic, the aesthetic experience of the public fomented insights about our interference on another complex systems, such as the big cities or the natural environment.

But also, it provided deep reflections about how we are here and the origin of the species. Because of that, it achieved an unexpected scientific audience, used by teachers to discuss the Theory of Evolution by Natural Selection, used to help the students to understand this process by experimenting it, despite its artificial and impossible nature. This illustrates the intricated role of Art in relation to Science, corroborating Galanter's statement that Art practice includes a large body of heuristics that simulates human experiences, and each technique suggests a hypothesis worthy of scientific investigation [31].

References

1. Galanter, P.: Truth to process – evolutionary art and the aesthetics of dynamism. In: International Conference on Generative Art. Generative Design Lab, Milan Polytechnic, Milan (2009)
2. Galanter, P.: What is generative art? Complexity theory as a context for art theory. In: International Conference on Generative Art (2003)
3. Galanter, P.: The problem with evolutionary art is… In: EvoCOMNET 2010: The 7th European Event on the Application of Nature-inspired Techniques for Telecommunication Networks and other Parallel and Distributed Systems (2010)
4. Takagi, H.: Interactive evolutionary computation: fusion of the capabilities of EC optimization and human evaluation. Proc. IEEE **89**(9), 1275–1296 (2001)
5. Werner, G.M., Todd, P.M.: Frankensteinian methods for evolutionary music composition. In: Griffith, N., Todd, P.M. (eds.) Musical Networks: Parallel Distributed Perception and Performance. MIT Press/Bradford Books, Cambridge (1998)
6. Galanter, P.: Complexism and the role of evolutionary art. In: Romero, J., Machado, P. (eds.) The Art of Artificial Evolution: A Handbook on Evolutionary Art and Music, pp. 311–332. Springer, Berlin (2008). https://doi.org/10.1007/978-3-540-72877-1_15
7. Gell-Mann, M.: What is complexity? Complexity **1**, 16–19 (1995)
8. Dawkins, R.: The Blind Watchmaker. Norton & Company, New York (1986)

9. Gardner, M.: Mathematical games: the fantastic combinations of John Conway's new solitaire game "Life". Sci. Am. **223**, 120–123 (1970)
10. Silva, T.B.P.: Thoughts upon the morphogenesis. In: Fragoso, M.L.P.G., Silva, T.R.F., Nobrega, C.A.M. (eds.) Computer Art & Design for All, 1st edn., vol. 1, pp. 159–167. EBA - Escola de Belas Artes de UFRJ/RioBooks, Rio de Janeiro (2014)
11. Holland, J.H.: Hidden Order: How Adaptation Builds Complexity. Helix, Reading (1995)
12. Konar, A.: Artificial Intelligence and Soft Computing - Behavioral and Cognitive Modeling of the Human Brain. CRC Press, Boca Raton (2000)
13. Bonabeau, E., Dorigo, M., Theraulaz, G.: Swarm Intelligence: From Natural to Artificial System. Oxford University Press, New York (1999)
14. Turing, A.M.: The chemical basis of morphogenesis. Philos. Trans. R. Soc. London. Ser. B Biol. Sci. **237**(641), 37–72 (1952)
15. Einstein, A.: On the motion of small particles suspended in a stationary liquid, as required by the molecular kinetic theory of heat. Ann. Phys. **17**(8), 549–560 (1905)
16. Michalewicz, Z.: Genetic Algorithms + Data Structures = Evolution Programs. Springer, Heidelberg (1998)
17. Russel, S.J., Norvig, P., Davis, E.: Artificial Intelligence: A Modern Approach. Prentice Hall, Upper Saddle River (2010)
18. Glover, F., Kochenberger, G.A.: Handbook of Metaheuristics. Kluwer Academic Publishers, Boston (2003)
19. Lehman, J., Stanley, K.O.: Exploiting open-endedness to solve problems through the search for novelty. In: ALIFE, pp. 329–336 (2008)
20. Lehman, J., Stanley, K.O.: Abandoning objectives: evolution through the search for novelty alone. Evol. Comput. **19**(2), 189–223 (2011)
21. Silva, T.B.P.: Morfogênese: sistema autopoiético emergente de vida artificial 293, [13] p. Thesis (doctorate) - University of Brasília, Institute of Arts, Postgraduate Program in Art (2014)
22. Moore, D.S.: The Basic Practice of Statistics, 5th edn. W. H. Freeman and Company, New York (2010)
23. Silva, T.B.P.: Intentionnalité & perception esthétique dans le système de l'art computationnel. In: D'Angelo, B., Soulages, F., Venturelli, S. (eds.) Esthétique & Connectivité, 1st edn., vol. 1, pp. 105–118. L'Harmattan, Paris (2018)
24. Birkhoff, G.D.: Aesthetic Measure. Harvard University Press, Cambridge (1932)
25. Eysenck, H.J.: The empirical determination of an aesthetic formula. Psychol. Rev. **48**, 83–92 (1941)
26. Berlyne, D.E.: Aesthetics and psychobiology. New York, Appleton-Century-Crofts, Educational Division, Meredith Corporation (1971)
27. Martindale, C.: Aesthetics, psychobiology, and cognition. In: Farley, F., Neperud, R. (eds.) The Foundations of Aesthetics, Art, and Art Education, pp. 7–42. Praeger, New York (1988)
28. Nadal, M.R.: Complexity and aesthetic preference for diverse visual stimuli. Doctoral Thesis, Department de Psicologia, Universitat de les Illes Balears (2007)
29. Nadal, M.R., Munar, E., Marty, G., Cela-Conde, C.J.: Visual complexity and beauty appreciation: explaining the divergence of results. Empir. Stud. Arts **28**(2), 173–191 (2010)
30. Schrödinger, E.: What is life? The physical aspect of the living cell. Based on lectures delivered under the auspices of the Dublin Institute for Advanced Studies at Trinity College, Dublin (1943)
31. Galanter, P.: Against reductionism: complexity science, complexity art, and complexity studies. Institute for the Study of Coherence and Emergence, Complexity and Philosophy Workshop (2002)