



On Evolutionary Computer-Generated Art

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Many people have a distorted view of Artificial Intelligence (AI). As Astro Teller observes, for most people “Artificial Intelligence is the science of how to get machines to do the things they do in the movies.”¹ AI researchers often have to deal with misconceptions created by the doomsday scenarios portrayed in movies such as the 1983 classic *War Games* or the *Terminator* series. These movies provoke fear. Others present a romantic view of AI. For instance, the 1984 movie *Electric Dreams* is about a boy who bought a computer and accidentally spilled a beverage on it. As a consequence, the computer developed AI. Listening to the girl next door practicing the cello, it learned how to play and compose music, fell in love with the girl, tried to kill its owner, and ended up committing suicide.

In reality, since its inception, AI research has given considerable emphasis to logic, reasoning, problem solving, planning, natural language processing, expert systems, chess, et cetera. In several tasks requiring intelligence, state-of-the-art AI systems are now able to attain human competitive results or even to surpass human performance. Yet, in tasks requiring creative reasoning, such as art, design, music, and poetry, computers are far from reaching the accomplishments of humans. As Dissanayake observes, art-making activities are ubiquitous, have evolutionary value, and are a part of human behavior since prehistory.² Creativity is often regarded as one of the most remarkable characteristics of the human mind. Not surprising, then, that the search for computational “creativity” should be a central aspect of AI.

During the initial years of AI research, the main source of inspiration was human intelligence. Over the years, researchers have realized that many other sources of inspiration can be used. Establishing analogies with physics phenomena gave rise to novel search methods such as Simulated Annealing,³ Hopfield Networks,⁴ and Elastic Networks.⁵ Currently, there is a growing interest in bio-inspired computing, an area of research that comprises techniques such as Evolutionary Computation (EC), Swarm Intelligence, Ant Colony Optimization, and Artificial Life.

Through time, evolution has created a wide variety of species adapted to their environment. Some of these species—for example, humans—exhibit intelligent behavior. Since evolution is the source for natural intelligence, it



naturally became a source for AI. According to Darwin, evolution is based on two fundamental principles: selection, and reproduction with variation.⁶ Selection ensures that fitter individuals are more likely to reproduce. The descendants of these individuals inherit characteristics from the progenitors—which implies that they tend to be fit—but they are not exact copies, which allows evolution. The reinterpretation of Darwin’s ideas in light of Mendel’s genetics, that is, neo-Darwinism, explains how characteristics are inherited and how and why changes occur. Natural selection occurs at the phenotypic level, while reproduction acts on the genotype.⁷ The characteristics of the individuals are not directly inherited. Instead, the genes that codify these characteristics and those that enabled their development are inherited. Variation results from copying errors—that is, mutations—and from the recombination of the genetic material of the progenitors.

The goal of EC research can be synthesized as follows: “How do we turn Darwin’s ideas into algorithms?”⁸ Nowadays, EC comprises a wide and growing variety of stochastic algorithms. In spite of this variety, they have the same main characteristics, so they can all be seen as instances of a generic evolutionary algorithm (see algorithm 1).

Algorithm 1 Generic Evolutionary Algorithm

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P ← generate-initial-population ()
while termination criteria not met do evaluate (P)
P' ← select-individuals (P(t))
P'' ← apply-genetic-operators (P')
P ← create-next-population (P,P'')
end-while
return simulation result
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To illustrate how such an algorithm would work, we’ll look at the Four-Color Map problem, which consists in coloring a map using a maximum of four colors in a way that ensures that no country has a neighbor with the same color.⁹ Using EC to solve this problem implies a series of analogies. Each individual is a *candidate solution* to the problem. In other words, each individual is a colored map. The fitness of an individual is proportional to the quality of

the solution. Thus, a colored map where no neighbors share the same color has maximum fitness, while map-colorings that violate this constraint will be penalized proportionally to the number of times they violate it.

To apply EC, one must find an adequate representation. For instance, one can consider that the genotype of each individual is composed of a chromosome, represented by a string, composed of n genes, where n is the number of countries in the map. Genes can assume four values, representing the color associated to the corresponding country.

Once the representation is chosen, one must also define adequate genetic operators. When two progenitors reproduce there is a probability, for example, 70 percent, of recombination of their genetic code. When recombination does not occur, the genetic code of the descendants is a copy of the progenitors’ code. For the purpose of recombination one could use 1-point crossover: a number (x) between 1 and n is randomly selected, and two descendants are generated by copying the first x genes from the first parent and the remaining genes from the second (and vice versa for the second individual). After this stage, the mutation operations take place. Each gene of the descendants has a probability of suffering a mutation, for example, 1 percent. Mutation can be implemented as follows: the value of that gene is replaced by a randomly chosen number between 0 and 3.

One must also define a selection scheme. Tournament-based selection is appropriate for this problem, that is, to choose a progenitor, one starts by randomly selecting a given number of individuals (e.g., five) among the population, and the fittest of these individuals will be the progenitor. An individual may be selected more than once for reproduction.

Finally, one must define an initialization method, a replacement scheme, and a termination criterion. For the sake of simplicity one can assume that an initial population of a particular size (e.g., one hundred) individuals is created by randomly choosing values for their genes; non-elitist generational replacement, that is, each population of individuals is entirely replaced by its descendants; and the simulation will stop when the map-coloring with maximum fitness is found.



1 Considering these choices, the algorithm would
2 proceed as follows. An initial population of one hundred
3 randomly generated individuals is created. Each of the
4 population's individuals is evaluated and its fitness deter-
5 mined. Fifty pairs of individuals are selected as progenitors
6 by using tournament selection; individuals may be selected
7 more than once. These generate one hundred descendants
8 by the application of the genetic operators described earlier.
9 The descendants replace the progenitors, thus becoming the
10 current population. The cycle is repeated, from the evalua-
11 tion step, until a map where no neighboring countries share
12 the same color is found.

13 Currently the most prominent EC approaches are
14 Genetic Algorithms (GAs), invented by Holland, and Genetic
15 Programming, popularized by Koza.¹⁰ The most significant
16 differences between these approaches concern representa-
17 tion and genetic operators. In a GA, the genome codifies
18 a set of parameters or characteristics necessary to build the
19 phenotype and is typically represented by a string. Thus,
20 the described map-coloring approach is a GA. In GP the
21 genotypes are programs—typically represented by a tree-like
22 structure—the execution of which results in the phenotype.

23 To a large extent, the appeal of EC is its independence
24 from problem-specific knowledge. Thus, one does not need
25 to know how to solve a problem; the only requirements for
26 applying EC are finding an adequate encoding and a way to
27 assign fitness. Likewise, the ability to use EC in an artistic
28 domain depends on finding an adequate way to represent
29 and evaluate artistic objects.

30 In his 1986 book *The Blind Watchmaker*, Richard
31 Dawkins delineates a program that allows the evolution of
32 the morphology of “virtual creatures” or *biomorphs*.¹¹ More
33 precisely, each biomorph is a drawing, the appearance of
34 which depends on the values of a set of parameters encoded
35 in a string, the genotype. The biomorphs of the current
36 population are displayed on the screen, and the user indi-
37 cates his/her favorite ones. In other words, the user guides
38 the GA, which circumvents the need to develop a com-
39 putational fitness function. This influential work led to the
40 emergence of a new research area, evolutionary art.¹² Due
41 to the subjectivity inherent in artistic production, and the
42 subsequent difficulty of creating an algorithm capable of
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assigning fitness to an artwork, most evolutionary art systems
are also guided by the user.

Draves' *Electric Sheep*—the name pays tribute to Philip
K. Dick's novel *Do Androids Dream of Electric Sheep?*—is
one of the most notable evolutionary art projects.¹³ Like
Dawkins' biomorphs, *Electric Sheep* features a user-guided
parametric evolution model. In this case, the individuals
are “fractal flames,” a particular kind of fractal, invented by
Draves, that belongs to the so-called Iterated Function Sys-
tem category of fractals.¹⁴ The genotypes consist of several
hundreds of floating point numbers that encode parameters
for the fractal formula, controlling the scattering of the bil-
lions of particles that compose each image. *Electric Sheep* is a
distributed computing project currently involving more than
350,000 users. Acting as a screensaver, it takes advantage of
the computer's idle time to render the individuals, that is,
“sheep,” that are being evolved collectively. Interested users
can vote on their favorite sheep, thus shaping the course
of evolution.

In parametric evolution models, the genetic code is
a visual language defined by the designer of the system.
Therefore, “creating a parametric model implicitly creates a
set of possible designs or a solution space.”¹⁵ As such, these
systems tend to have an identifiable system *signature* that is
closely related to the choices made by the human designer.
The model should be compact, that is, genotypes should be
relatively small; expressive, meaning that it should allow a
wide variety of shapes; and robust, in the sense that interest-
ing images should be easy to find.¹⁶ Parametric evolution
has been applied to a wide variety of domains including
the evolution of cartoon faces,¹⁷ fonts,¹⁸ line drawings,¹⁹ sur-
faces,²⁰ and consumer product design.²¹

The seminal work of Sims gave rise to another popu-
lar evolutionary art approach: expression-based evolution.²²
In addition to Sims' work, notable examples of this tech-
nique include works by Latham, Rooke, and Hart.²³ (Hart's
work is on the cover of *TER*.) We shall use NEvAr (Neuro
Evolutionary Art) to illustrate this approach. Largely inspired
by the work of Sims, it allows the evolution of populations
of images, using GP as in Sim's work. Each genotype is a
program—in this case, a symbolic expression represented
as a tree. These programs are constructed from a lexicon



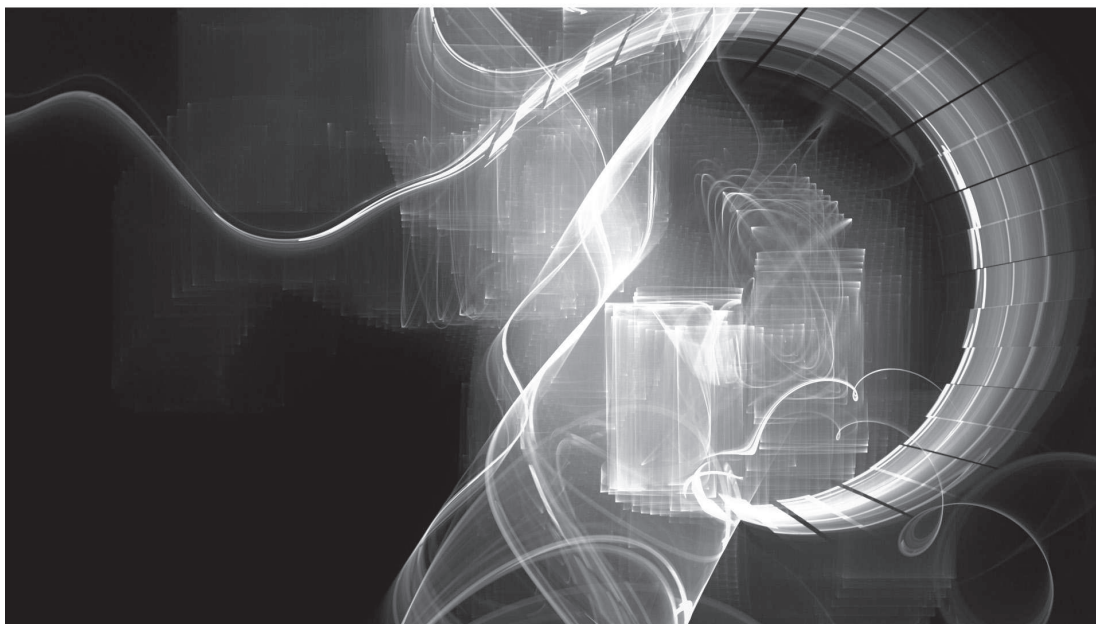
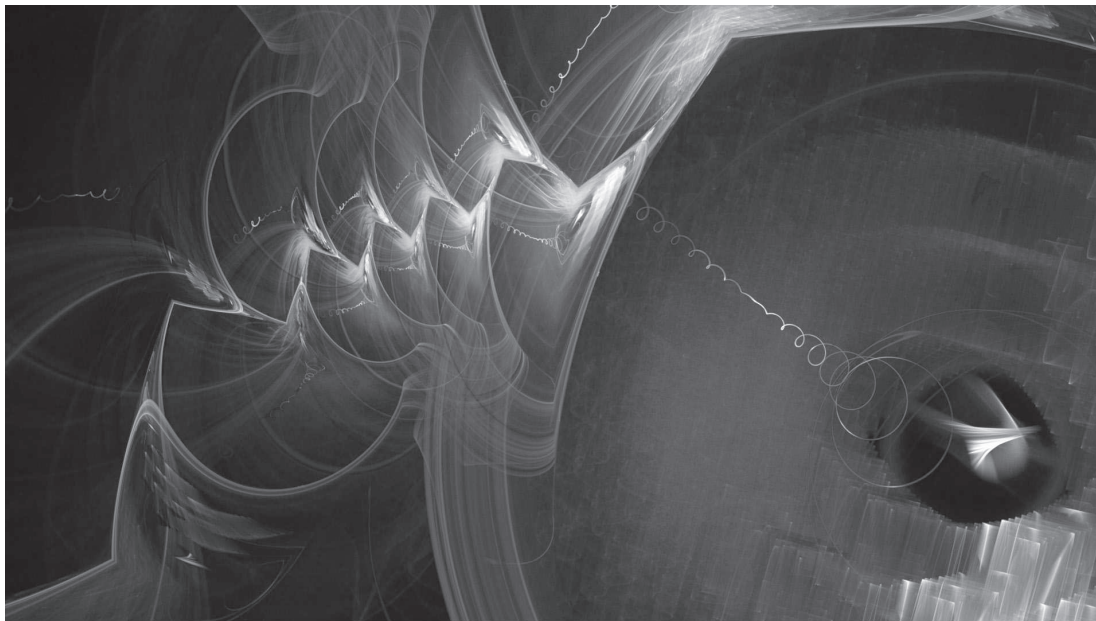


Figure 1. Still images from *Generation 243* by Scott Draves and the Electric Sheep (2009), commissioned by Carnegie Mellon University for the Gates Center of Computer Science

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1 of functions and terminals. The function set is composed
2 mainly of simple functions such as arithmetic, trigonometric,
3 and logic operations. The terminal set is composed of two
4 variables, x and y , and some random constants. The phe-
5 notype (image) is generated by evaluating the genotype for
6 each (x, y) pair belonging to the image. Thus, the images
7 generated by NEvAr are graphical portrayals of symbolic
8 expressions (see figure 2).

9 In order to produce color images, NEvAr resorts to
10 a special kind of terminal that returns a different value
11 depending on the color channel being processed. Recombi-
12 nation is performed using the standard GP crossover opera-
13 tor, which exchanges sub-trees between individuals.²⁴ Five
14 mutation operators are used: sub-tree swap, sub-tree replace-
15 ment, node insertion, node deletion, and node mutation.²⁵

16 Like most, if not all, evolutionary art systems, NEvAr
17 has a signature—in the sense that it is more prone to gen-
18 erate certain types of images than others—that is closely
19 related with the function set, genetic operators, and gen-
20 otype-phenotype mapping used. Nevertheless, as demon-
21 strated by Machado and Cardoso, it is theoretically possible
22 to generate any image with NEvAr, and the same is true
23 for several other expression-based evolutionary art systems.²⁶
24 This means that “Every great (and not so great) work of
25 visual art is in there, past, present and future, as are images
26 of political assassinations, nude celebrities (even ones that
27 have never posed nude), serial killers, animals, plants, land-
28 scapes, buildings, every possible angle and perspective of our
29 planet at every possible scale and all the other planets, stars,
30 galaxies in the universe, both real and imaginary. Pictures
31 of next week’s winning lottery ticket, and of you holding
32 that winning ticket.”²⁷

33 In practice, the images tend to be abstract and have a
34 computer-generated appearance. Nevertheless, a patient and
35 disciplined user is able to guide evolution from an initial,
36 randomly generated population, to populations of images
37 that meet the users’ preferences.

38 Recently, Graça and Machado have developed “Evolv-
39 ing Assemblages,” a system that evolves large-format repro-
40 ductions of input images by assembling 3-D objects, using
41 GP and interactive evolution.²⁸ In this case, each individual
42 is a program that receives an image as input and generates
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an assemblage as output. To accomplish this, each genotype
comprises five trees. Based on the input image and for each
of its pixels, the first tree selects, from a list of available
objects, which type of object will be placed on the canvas;
the second tree determines the rotation applied to each
object; the third one determines the size of each object; the
fourth one determines the x coordinate where the object
will be placed; and, finally, the fifth one determines the y
coordinate. Once the assemblage is calculated, the color of
objects is determined: each object assumes the color of the
pixel of the input image where its center is placed.

GP approaches have also been used in domains such
as the evolution of painterly renderings,²⁹ line-based draw-
ings,³⁰ plant-like shapes and other 3-D objects,³¹ l-systems
(see McCormack for a survey³²), filters,³³ animations,³⁴ and
architectural plans.³⁵

Outside the field of the visual arts, evolutionary
approaches based on GAs or GP have been applied to
sound synthesis, improvisation, harmonization and compo-
sition (see Miranda and Biles for a survey³⁶); poetry genera-
tion³⁷; choreography;³⁸ and many other fields. (See figures
3, 4, and 5.)

Although interactive evolution techniques have been
used to produce a wide variety of artistic artifacts, this pres-
ents several problems. The most pressing problem is the user
fatigue caused by the need to evaluate a large number of
individuals.⁴⁰ Other problems include the subjectivity of the
task, the lack of consistency in the users’ evaluations, and the
bias toward novelty. All these factors have a negative effect
on the evolutionary process. Moreover, interactive evolution
techniques skirt an important AI objective: building a com-
putational system capable of performing aesthetic judgments,
even if limited ones.

In general terms, there are three main approaches for
the automation of the fitness assignment step of evolution-
ary art systems: using handwritten fitness functions; using
machine learning techniques and using co-evolutionary
approaches.

Machado and Cardoso took inspiration from the
works of Arnheim as well as from research that points
toward a preference for simple representations of the world,
and a tendency to perceive it in terms of regular, symmetric



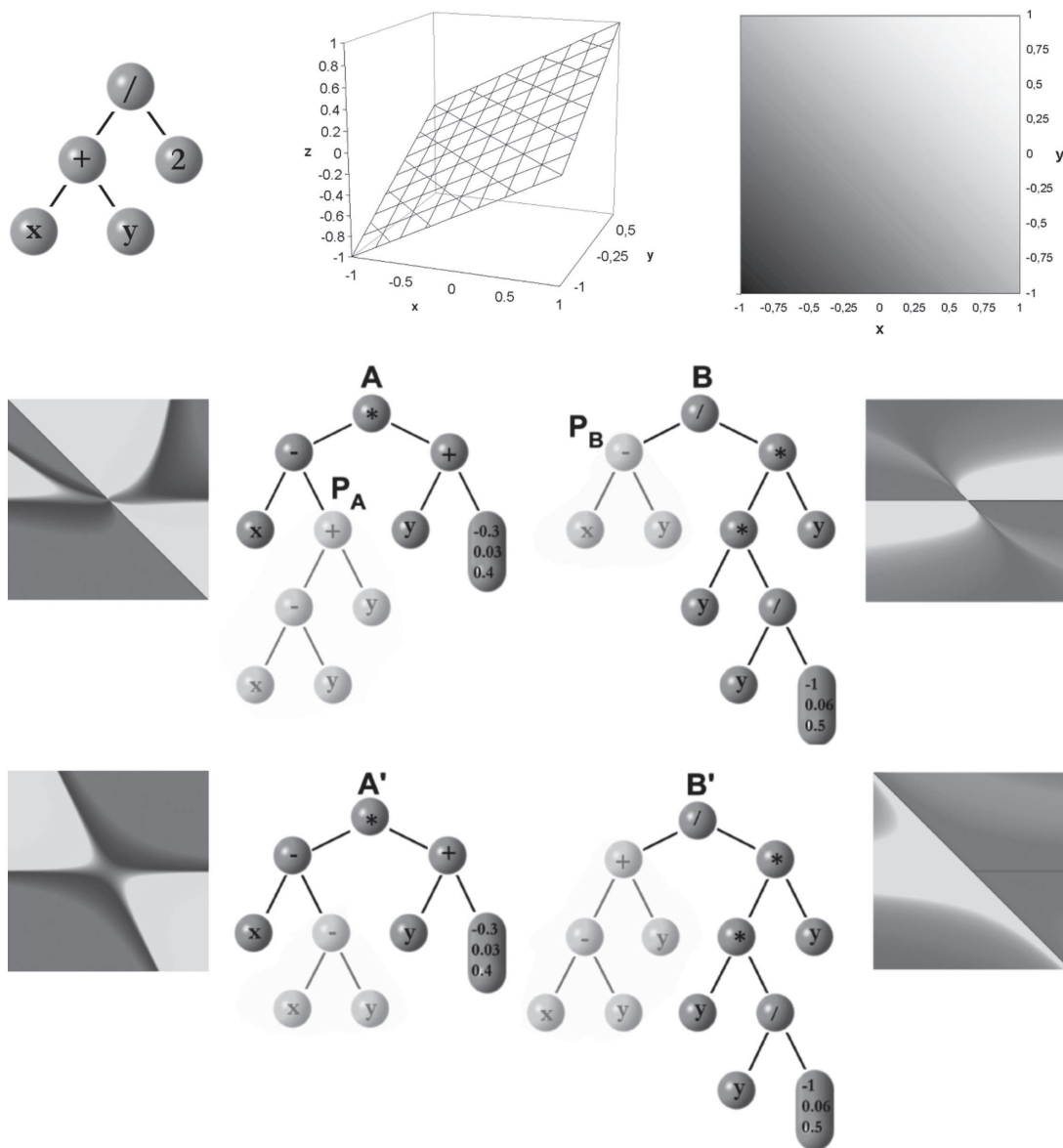


Figure 2. In the top row: function $f(x, y) = (x + y) / 2$ represented as a tree (the format of the genotype); as a 3-D chart and as an image produced by assigning to each pixel a luminance proportional to the height of the corresponding position of the 3-D chart. In the second row: two individuals and their corresponding genotypes. In the third row: the descendants produced by performing a crossover operator at points P_A and P_B and swapping the corresponding sub-trees (depicted in lighter gray).



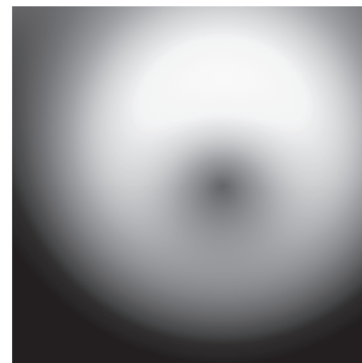


Figure 3. Images from the series *bodies of sin* created with NEvAr using interactive evolution. These images are, arguably, the first set of pictorial images created using expression-based evolution and were first displayed at EvoMUSART'2005, Lausanne, Switzerland.





Figure 4. Assemblages evolved by Graça and Machado in the scope of the *Evolving Assemblages* project, which won the 2010 Genetic and Evolutionary Computation Conference Evolutionary Art Competition.



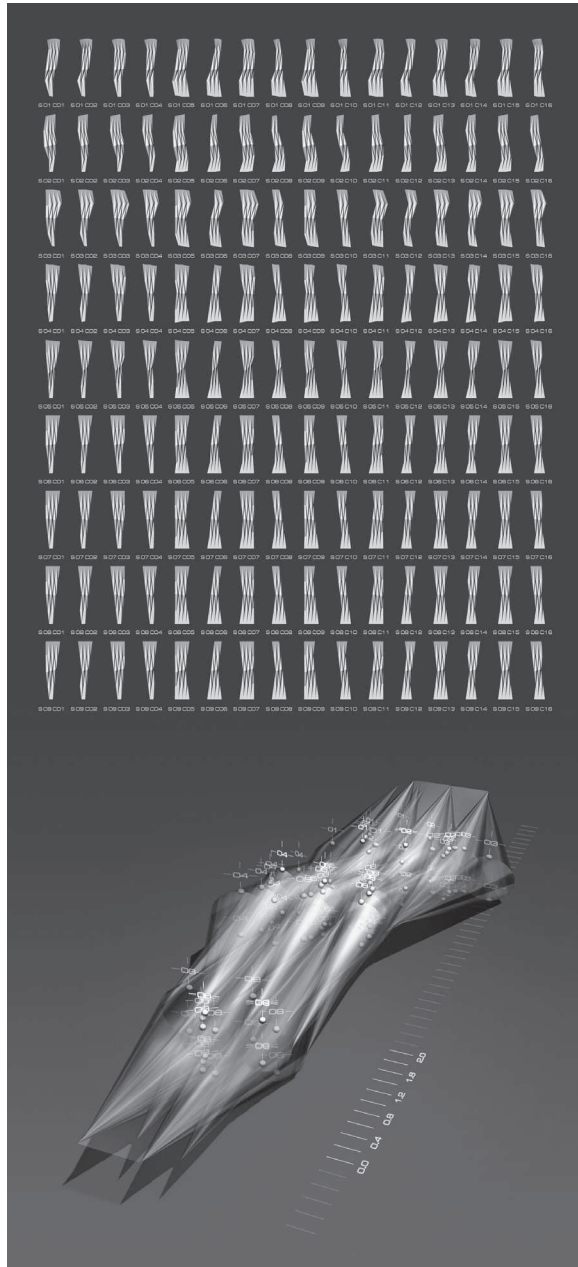


Figure 5. Morphogenetic design experiment—AA Strawberry Bar, 2003, Achim Menges, using Genr8.³⁹

and constant shapes.⁴¹ As a consequence, they have explored the working hypothesis that aesthetic value has a link with the sensorial and intellectual pleasure experienced in finding a compact percept (internal representation) of a complex visual stimulus. The identification of symmetry, repetition, rhythm, balance, et cetera, can be a way of reducing the complexity of the percept, which may explain these aesthetic principles and the ability of the brain to recognize them in an “effortless” way.

Following this set of ideas, in “Computing Aesthetics,” we propose an aesthetic theory: those images that produce a complex visual stimulus and yet result in a compact percept—that is, a compact internal representation—tend to be valued.⁴² For instance, fractal images are usually complex, and highly detailed; yet they can be compactly described by a simple mathematical formula. The self-similarity of these images can make them easier for our brain to process, allowing one to build a compact percept, which would explain, according to this theory, why fractal images tend to be aesthetically interesting.

To test this theory, we used JPEG- and quad-tree-based fractal image compression to estimate the complexity of the visual stimulus and the percept.⁴³ In “All the Truth,” we used a variation of the proposed formula to assign the fitness, thus making NEvAr autonomous.⁴⁴ In recent years, several evolutionary art systems that use complexity estimates to assign fitness have been proposed. Neufeld, Ross, and Ralph present a genetic programming engine generating non-photorealistic filters by means of a fitness function based on Ralph’s bell curve distribution of color gradient.⁴⁵ The model was implemented by doing an empirical evaluation of hundreds of artworks. Their paper contains examples of some of the non-photorealistic filters created. In one of his works, Greenfield uses geometric measurements induced by the color organization of the images.⁴⁶ The algorithm reduces the images to a small number of regions of the same color. Fitness is assigned by performing a weighted sum of three geometric assessments of these regions: the sum of their areas, of their boundary lengths, and of the adjacencies among them. In a later work, Greenfield used a multiple-objective optimization approach to fitness assignment.⁴⁷ The goal was to maintain several “species” within



the same population of images. He defines multiple static fitness functions. Each of these functions uses two out of three previously described assessments. Since the assessments are incompatible, this fosters the specialization of the individuals and the appearance of species.

The first attempt to fully automate an evolutionary art system appears in the work of Baluja, Pomerlau, and Todd.⁴⁸ They begin by using interactive evolution to build a set of images evaluated by users. In a later stage, they use machine-learning techniques, namely, Artificial Neural Networks (ANNs). ANNs are inspired in the structure and functional aspects of the brain. They are composed by a set of interconnected (artificial) neurons, and have been used successfully in a wide variety of tasks, including time series prediction, robotic controllers, and face and character recognition. The appeal of ANNs is their ability to learn from a set of examples. Baluja and colleagues use the set of images evaluated by the user to train an ANN, which is meant to learn the preferences of the users. Although the authors classify the results as “somewhat disappointing,” this work is an important step toward the automation of fitness assignment.

Saunders and Gero use a Self-Organizing Map ANN to assign fitness to the images produced by an expression-based evolutionary system.⁴⁹ Self-Organizing Map ANNs do not require a training step; they automatically organize the input data—in this case, images—into clusters according to their similarity. (It is important to notice that this computational similarity may be significantly different from similarity as perceived by humans.) The goal of their system is to study the emergence of novelty. As such, fitness depends on the dissimilarity of an image to the existing clusters of images. In general terms, the experimental results indicate that their evolutionary algorithm tends to produce increasingly complex images.

The work of Saunders and Gero also has a co-evolutionary inspired component. They use an agent-based framework, where each artificial agent has its own expression-based evolutionary system and Self-Organizing Map. When an agent finds an image that has the “right” degree of novelty, it shares the genotype with other agents. If a receiving agent also finds the image adequately novel, the genotype is included in the population of its evolutionary

system and the receiving agent issues a credit to the agent that discovered the image. Thus, although there is not a direct arms race among agents, agents influence each other by communicating the genotypes of the artworks they produce to other agents.

Rooke was the first one who made an attempt to use a co-evolutionary approach in the context of evolutionary art, but he never published the results of these experiments. Gary Greenfield states that “Rooke’s idea was to try to co-evolve a population of art critics, which he called ‘image commentators,’ to perform the aesthetic evaluations of the images his Sims’ inspired system generated.”⁵⁰

Greenfield implemented an interesting solution to the automation of the fitness assignment. He co-evolves a population of images, using an expression-based evolutionary system, and a population of convolution image filters. For determining fitness, the filters are applied to the images, possibly changing them. The fitness of an image is proportional to the amount of change introduced by the filters. The fitness of a filter is inversely proportional to the changes it introduces in the population of images. Thus, in simple terms, each filter acts as a “parasite” and its survival depends on the ability to pass unnoticed. On the other hand, the fitness of an image depends on its ability to identify the parasites, by making them visible. This co-evolutionary setup tends to converge toward states where white-noise images are predominant. Nevertheless, a given type of imagery is, typically, unable to dominate the population for too long because of the evolutionary pressure caused by the parasites. This constant tension generates an interesting evolutionary dynamic.

The latest development of NEvAr is also inspired by co-evolution. Like Baluja and colleagues, we employ ANNs. However, there is an important difference: by employing a set of metrics—for example, complexity estimates—we measure several characteristics of the images; the ANNs base their judgments on the characteristics of the images. Thus, in simple terms, the ANNs never see the images; they only have access to their characteristics. By these means, the training of the ANNs is performed using information of a higher level of abstraction than the images’ pixels.

The goals of this setup are twofold: first, the creation of images without human intervention. The only



1 information provided to the system is a set of images—in
2 this case five thousand paintings made by renowned art-
3 ists—that acts as an aesthetic reference. Second, the creation
4 of a system that systematically explores new styles. For this
5 purpose, we employ a method, inspired by co-evolution
6 that promotes stylistic change from one evolutionary run
7 to the next.

8 The ANNs are trained by showing them two classes
9 of images: a set of paintings by well-known authors and
10 a set of images generated randomly by NEvAr. Once this
11 is done, an evolutionary run is initiated and the trained
12 ANNs are used to assign fitness to the images evolved by
13 NEvAr. The evolved images that the ANNs fail to identify
14 as being produced by NEvAr have maximum fitness. The
15 goal is twofold: first, to evolve images that relate to the
16 aesthetic reference provided by the first class, which can be
17 considered to be an inspiring set; second, to evolve images
18 that are novel in relation to the imagery typically produced
19 by the system. Thus, rather than trying to replicate a given

style, the goal is to break away from the traditional style
of the system. Once novel imagery is found—that is, when
NEvAr is able to find images that the classification system
fails to classify as being created by NEvAr—these images
are added to the second class, the classifier is retrained and
a new evolutionary run begins. This process is iteratively
repeated and the method fosters a permanent search for
novelty and deviation from previously explored paths.

In our last experiment, the system performed twelve
consecutive evolutionary runs.⁵¹ During these runs, the arms
race between the ANNs and the evolutionary system was
always balanced: the evolutionary engine was always able to
find images that were misclassified by the ANNs. However,
after these were added to the set of training images, the
ANNs were always able to discriminate between the images
created by evolution and the set of paintings (with a success
rate above 98 percent), thus fostering a stylistic change in
the next evolutionary run. Additionally, we conducted some
tests using the ANNs from different iterations to classify

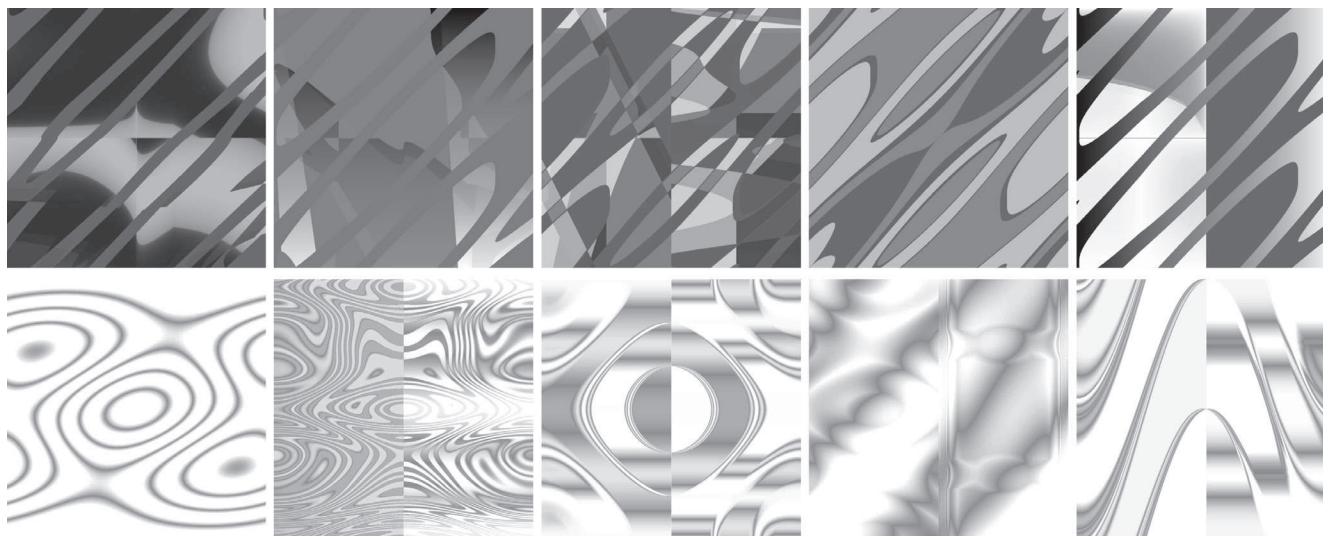


Figure 6. Examples of images created using NEvAr's approach to stylistic change. The images in the top row characterize the type of imagery being produced during the first evolutionary run of the process; the ones in the bottom row depict the style of the eleventh evolutionary run of the experiment.



external imagery that did not belong to the training sets. The experimental results show a gradual improvement of performance as the number of runs increases. This result indicates that the competition between systems improved not only the performance of the ANNs but also their generalization abilities. The evaluation of the aesthetic merit of the evolved images is subjective. Nevertheless, it is reasonable to state that in each run evolution converged to a consistent style of imagery, and that the evolved styles are all significantly different from each other. Hence, the main goals of the approach were attained.

The assessment of the aesthetic merit of the evolved images is subjective; therefore we provide examples of images evolved during the first and twelfth evolutionary runs. The CD accompanying the handbook *The Art of Artificial Evolution* includes the thirty thousand images evolved in the course of this experiment.⁵² Additionally, it is safe to say that in each run evolution converged to a consistent style of imagery, and that the evolved styles are all significantly different from each other.

Evolutionary art research is reaching maturity, and part of this process is the growing awareness of the various social, artistic, and scientific challenges the area faces. From a social standpoint, building tools that foster the creativity of the user is probably the most prominent goal. From an artistic perspective, the greatest challenge is the acceptance of the evolutionary approach as a significant art practice. Promoting the participation and close involvement of artists in the design of these systems is crucial for meeting this challenge. From a scientific standpoint, the most important challenges include the automation of fitness assignment, the creation of systems that develop their own aesthetics, the integration and interaction of these systems in a cultural environment, and the pursuit of new forms of human-machine interaction.

Evolutionary art results in dynamic models whose behavior is neither totally defined nor predictable by the model's creator. In fact, since the only requirement is having a way to assign fitness, EC allows the discovery of solutions to problems for which very little knowledge is available. This allows their application to creative tasks, such as art, that we are—and might always be—far from fully understanding.

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