Algorithmic Art: Technology, Mathematics and Art

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Abstract. *This paper describes algorithmic art, i.e. visual art created on the basis of algorithms that completely describe generation of images. Algorithmic art is rooted in rational approach to art, technology and application of mathematics. It is based on computer technology and particularly on programming that make algorithmic art possible and that influences it most. Therefore we first explore relations of technology and mathematics to art and then describe algorithmic art itself.*

Keywords. Art, Technology, Computer, Mathematics, Algorithmic Art.

1. Introduction

Algorithmic art is visual art generated on the basis of algorithms that completely describe generation of images. This kind of art is strongly related with contemporary computer technology and especially with computer programming. Another influence to algorithmic art is related with mathematics that is used in algorithms for image generation.

It is clear that it is technically possible to produce images by computer programs based on some algorithm. However, the question is whether under such strong constraint that image has to be created by an algorithm (instead of e.g. use image processing tools like Photoshop where human hand can be involved in creating the image) it is possible to create interesting, original or even aesthetically valuable visual works.

Interesting thoughts about producing artworks under constraints come from the famous Russian composer Igor Stravinsky in his essay "The Poetics of Music» [12]. Stravinsky literally wrote: «My freedom thus consists in my moving about within the narrow frame that I have assigned myself for each one of my undertakings". And he also added even more strongly: "I shall go even further: my freedom will be so much the greater and more meaningful the more narrowly I limit my field of action and the more I surround myself with obstacles».

So it is not quite sure whether to start painting on a blank paper without any constraints is necessarily easier than to have a constraint that, for example, you only use squares of two sizes.

The rest of this paper is organized as follows: In Section 2 we describe relations between art and technology, while Section 3 presents the role of computer technology in development of digital art, and particularly of algorithmic art. Section 4 discusses rational approach to art by presenting approaches of several well known artists. In section 5 rich relations of mathematics and art is described. Section 6 presents the role of algorithms in generation of visual art pieces from the technical side, while Section 7 gives an overview of algorithmic art, its history and main proponents. Finally, Section 8 presents conclusions.

Author of this paper used some of the materials from his earlier texts [2] and [3].

2. Art and technology

Visual arts have seen birth of a number of technologies, especially in the last six centuries. Some of them are gravure (invented around 1400), print (1440), lithography (1796), photography (1830) and serigraphy (1920).

Development of new technologies was always a stimulus for artists to try to use them for creation of new expression, expression that was not possible with existing technological tools. Although technology is a medium for artistic work, new tools for work very often become inspiration for new approaches and give birth to new ideas. Visual art is e.g. hardly imaginable without Albrecht Dürer's engravings, but the fact is that artists before 1400th didn't have gravure at their disposal.

Modern technologies based on computers and communication, developed in the second half of 20th century, gave a new powerful stimulus for developing of fresh expression. On the first place are computers, then various input devices like mouse or scanner, various output devices like screens, inkjet printers or 3D printers, image processing tools like Photoshop, Internet with its popular Web and email services, etc.

We will now analyse the main characteristics of computer generated art, also called digital art (although this title doesn't seem to be very appropriate in the era of digitalisation of everything including art).

3. Computer generated art

"Many years of exploration in art, science and technology have brought us such fields as computer graphics, computer animation and music, scientific visualization and multimedia design – all of which are having tremendous impact in the artistic, educational, research and commercial communities" – C. Harris, Editor of Leonardo Books

Let us first see what new features that were not present in earlier generations of visual technologies are specific for computer as a key tool for enabling computer generated art. To begin with, computer is the first tool for *symbol processing* in human history, and this means for processing of any kind of symbols humans use like numbers, characters, geometric figures and lines, images, sounds, etc.

Besides that computer is executing operations that are *programmed*. It can repeat a huge number of complex programmed operations extremely fast and precise. This gives the computer an enormous potential for support developing human creativity, the potential that no technology yet had. Programming and flexible processing of input information also enabled *interactivity*, again a completely new technological feature of considerable interest for art. Programming also enabled *animation*, a feature used in many art activities.

Besides, *networked computers* enabled communication, cooperation and transport of information on huge distances, and thus additionally increased abilities of information technology in many art fields.

Computer generated visual art is using potential of computers for generation and processing of visual and possibly also other information. Information can either be directly generated from programs or it can come from various input devices like scanners, mouse or different type of databases, to be processed either by image processing tools or by programs. Program generated or processed information is used in algorithmic art.

Graphical information that are generated by programs or processed after obtained from diverse input devices can be shown on different output devices like screens, printers or plotters. It is also possible to create dynamically changing image structures, e.g. graphical animations. Interactivity with computer can lead to constant changes in image structures that we see on the screen, e.g. as a consequence of changing the position of objects or their temperature distribution that are detected by appropriate sensors. Sensors continuously send this detected information to the computer program in charge that uses updated values of input variables and on the basis of them generate change of the image wee see.

Enormous potential of information and communication technologies led to numerous approaches to application of computers in visual arts. Some of these are digital imaging (creating 2D images), digital sculpture (creating 3D images using CAD type of tools), digital installations and virtual reality (e.g. interactive environments or data-driven installations that use real-time information obtained from Internet), performance and sound art, digital animation and video, software art (e.g. interactive drawing) and net art (various art forms that use Internet).

Description of different forms of digital art and presentation of numerous examples of these forms can be found in Bruce Wand's book «Art of the Digital Age» [15].

4. Art and rationality

"*A man paints with his brains, not with his hands*" *- Michelangelo*

Although art is often considered as an intuitive activity related mostly with emotions and inspiration, this is certainly not the only approach to art. Finally, artists have to learn about art theory, technology and techniques in order to have an appropriate background for creating artwork. All these are disciplines based on rational approach. But rational approach is primarily important in creation of artworks.

During the history of art numerous techniques were devised in order to obtained particular artistic effects. This is e.g. the case for pointillism and cubism. Thus Georges-Pierre Seurat developed pointillism as almost analytical technique in which painting is done using discrete colour dots with complementary colours being next to each other. Cubism devised technique of painting objects from several points of view that provided a novel view on portrayed objects. Studying of colour theory, light, and perception was also necessary in order to fully utilize colours and develop desired colouristic effects.

Perspective is another analytic achievement that enabled projection of three-dimensional objects onto a two-dimensional surface. Linear perspective was used by Islamic artists in the Middle Ages, and rediscovered in Italy in the 15th century, during Renaissance. Golden ratio, so popular in visual arts and architecture, is known from ancient times and was largely employed in Renaissance.

Rarely was a rational method of creation of an artwork described in such detail as in Edgar Alan Poe's essay "The Philosophy of Composition" [10]. In this text E. A. Poe gives reconstruction of steps of development of his famous poem "The Raven". He literary wrote that "… no one point in its composition is referable either to accident or to intuition", and that "the work proceeded step by step, to its completion, with the precision and rigid consequence of a mathematical problem". Here Poe described how he decided about the poem length, the effect to be expressed by the poem, the refrain and its sound ("Nevermore"), a creature repeating his sound (Raven), etc.

Now we will concentrate on relation of art with mathematics, one of strongest building block of human rational thought.

5. Art and mathematics

"A mathematician, like a painter or poet, is a maker of patterns" - G. K. Hardey, 20th century mathematician

"Mathematics is an invisible art form of profound social and scientific significance. Computer graphics make mathematics visible" – H. Ferguson, sculptor

Mathematics and science had influenced arts from ancient times: e.g. façade of Parthenon built in the fifth century B.C. contains a number of proportions such as the golden ratio and the square root of 2, while periodic patterns frequently occur in the Islamic and Moorish ornaments. However, it was only in Renaissance that artists began using science and mathematics more intensively. They were influenced by the rediscovery of Greek philosophy and were convinced that mathematics was the true essence of the physical world and that the universe was ordered and explainable in geometric terms [7]. Thus for example two famous Renaissance artists, Leonardo da Vinci and Albrecht Dürer were studying and using knowledge on perspective, human body proportions (especially da Vinci), optics and science of colours in creation of their works.

Another Renaissance figure, Pierro dela Francesca, well-known painter from the 15th century was one of the greatest authorities for perspective. He "… had a passion for geometry and planned all his works mathematically to the last detail. The placement of each figure was calculated so as to be correct in relation to other figures and to the organization of the painting as a whole". [4]

However, by far the most intensive influence of mathematics and science on arts began in recent times, in the 20th century. And it was not used only in visual arts – one example from the music field is a Hungarian composer Bela Bartok who applied golden section and Fibonacci sequence in some of his works.

Importance of mathematics for artists is emphasized by Max Bill in his well-known text on the mathematical approach in contemporary art [1]. He wrote that he is convinced that "it is possible to evolve a new form of art in which the artist's work could be founded to quite a substantial degree on a mathematical line of approach to its content".

The best known 20th century artist that was influenced by mathematics was probably M. C. Escher. Although he was not mathematically trained he was interested in mathematics. In mid 1930th he started to develop mathematical approach to structure of his prints, and in construction of his famous "impossible objects" prints he was influenced by mathematician Roger Penrose and his father L. S. Penrose. In his works Escher developed strange perspectives and perspectives on the sphere, and studied the use of tessellations of a plane (i.e. regular periodic divisions of a plane), convergence to a limit, various transformations of shapes as well as Möbius strip.

His works illustrate the result of his attempts to visually express various mathematical concepts like infinity, duality, recursion and self-similarity. The first stage in process of creation of his works Escher devoted to developing a geometric model of image. Escher wrote about his work in this field in the lecture about the "Regular division of a plane" [5].

Development of computer technology and particularly graphic cards and software in the second part of the 20th century made an enormous influence on the ability of visualizing mathematics and using these visualizations in design and art.

One of the best known mathematical approaches created in the era of computer graphic and exceptionally suited for generating attractive visual structures are *fractals*, a family of self-similar (they appear similar at all levels of magnification) and scale invariant objects that have a simple recursive definition. Fractals were invented by a Polish-French mathematician Benoît Mandelbrot, and the term fractals that he coined was derived from the Latin *fractus* meaning "broken" or "fractured". He illustrated fractals with computer-based visualizations, and these images were so interesting that they soon became extremely popular. Mandelbrot also found that fractals are realistic models of many real world phenomena like mountains, coastlines, structure of plants and blood vessels, clustering of galaxies, Brownian motion and stock market prices.

Some interesting examples of fractals are Mandelbrot set and Julia set. Mandelbrot set is defined by a family of complex quadratic polynomials. It is a subset of a complex plane, i.e. a set of complex numbers or points in the complex plane the boundary of which does not simplify at any magnification. A picture of the Mandelbrot set can be made by different type of colouring, e.g. by colouring all the points which belong to the Mandelbrot set black, and all other points white. In the centre of the picture of the Mandelbrot set is the characteristic large cardioid-shaped region.

Various algorithms are used for producing computer drawings of the Mandelbrot set. They are quite simple, and e.g. the so called "escape time algorithm" has only about a dozen of steps. This is an example of a simple mathematical model generating complex results.

Some of the other mathematically based methods used for generation of attractive images are genetic algorithms and cellular automata. A number of interesting examples of cellular automata visualization are presented in the Stephen Wolfram's book "A New Kind of Science" [16]. Cellular automata are also used for generation of random numbers for the *Mathematica* software, which is an excellent example of complex structures generated by a simple algorithm.

Among interesting mathematically based artistic objects are sculptures based on mathematical objects as well as different type of perspectives painted on the sphere. One of the leading mathematically oriented sculptors is Helaman Ferguson, who is using mathematics as a design language for his sculptures [4]. Ferguson is also an internationally known mathematician whose algorithm has been listed as one of the top ten in the twentieth century. His sculptures in stone and bronze have been named "theorems in bronze and stone". They can be found on many public spaces and were shown in a number of exhibitions.

One of the leading artists working with perspectives painted on a sphere is Dick Termes. He developed his own six-point perspective system that he calls Termespheres, being "visual environments painted on the surface of spheres that hang and rotate from ceiling motors" [4]. These perspectives show everything that one can see from one point looking in all directions. It is well known that geometries that fit on the sphere are totally different from geometries that fit on the plane, and they are related to the study of polyhedra. Six-point perspective is related to the cubical polyhedron that extends in all six directions of the space. One of Termes's well-known works is "Paris Opera", acrylic on a polycarbonate sphere (40 cm diameter) that shows a six-point perspective view of Charles Garnier's design of a Paris Opera.

As can be seen, a lot of work in this field has been done with the goal of visualizing mathematical objects. This approach is certainly valuable for the sake of research in mathematics, but it doesn't necessarily lead to interesting visual solutions to the so called fine art or 'high art' [4]. Too much precision, symmetry or repetition may look attractive but often isn't regarded as art. However, mathematical approach can inspire artists to use their imagination and creativity and to use it in the process of creation artworks.

Another avenue is to use mathematics as a tool in developing artists' ideas. Following this approach artists typically use rather simple mathematics that enable accomplishment of their idea but is of no interest from the mathematical point of view. In such case a lot of experimenting is typically needed in order to achieve visually attractive result. It is this kind of approach that is often used in algorithmic art.

6. Algorithms in visual art

Algorithmic art is based on generation of visual artworks using *algorithms*, i.e. precise defined procedure that computer executes step by step. Algorithms are implemented in *computer programs* coded in some programming language. Algorithm, or computer program implementing it, describe the process of generation of image that we can see either on the screen or as printed. Program for image generation contains the author's *idea* about the image as well as the *technique* by which this idea is transformed into an image. It also has to define which graphical elements and their structures should be generated (straight or curved lines, shapes, a group of elements with a specified structure, etc.), what are values of their parameters (e.g. position of a rectangle, its dimensions and its elevation toward axes), colours of lines and shapes, etc.

An elementary algorithm for image generation could look like this: "come to a specified point, draw the rectangle of certain dimensions, elevation toward axes and colour; after that move to some other point and draw the circle …". Such algorithms use iteration procedures that describe related sequence of steps that execute specified actions, e.g. draw a network of squares with specified positions, sizes, colours, etc.

Technically, algorithms use computational structures such as loops, subprograms and recursion, as well as various mathematical expressions.

Algorithmic artists (also called "algorists") as a rule don't use special graphical software but rather *general program languages* that enable drawing basic graphical elements like line, circle or rectangle (and most programming languages, including various dialects of Basic language, have this feature). Such approach requires more work but as a reward offers much more flexibility and freedom in expression. Using general program languages algorists *develop their own software* in which they embed their artistic ideas. After the image is generated no further intervention with image processing tools like Photoshop is done. Interventions for changing image are done merely by changing the algorithm (i.e. the corresponding computer program).

The algorithms could also be executed by human hand, and they have been executed by humans before computers came into arena (and sometimes even after that). However, the evident advantage of computer and its output units is in enormous processing power of contemporary computers and precision of its output units. Because of that they can execute very complex algorithms that include a huge number of graphical operations in a rather short time and without mistake. This enables routine execution of algorithms that would require years to be executed by hand. All this gives computer technology a role of enabler of a real revolution in algorithmic art.

Another particularly important fact is that analysis of consequences of changes in the algorithm, i.e. in the corresponding computer program, is considerably simpler and faster in comparison with repeating of manual construction of somewhat changed image. This enables intensive experimentation needed for discovering the most appropriate artistic result.

Algorithmic approach to art existed in classical visual arts. Probably the best known example is M. C. Escher whose mathematical inclination was already mentioned here. Many of his artworks are structured in such a way that it is possible to write algorithms (computer programs) that generate them. This was indeed done by several authors from the computer science field. One example is Michael Trott who in his book "Mathematica Guidebook for Graphics" [13] constructed a computer program that generates image of the Escher's well-known lithograph Reptiles.

Works of op art pioneer Victor Vasarely were created on the basis of a deliberate plan of their structure and colouring, as can be seen from Vasarely's blueprints. Robert C. Morgan in his book «Vasarely» [9] wrote: «He created algorithmic systems that in many ways parallel the development of the computer», and also: «Vasarely made his own visual software in the form of mathematics, referring to the blueprints of his works as *programs*».

Since algorithmic art consists of generation of images on the basis of algorithms, algorithms can be viewed as a *notation*, and notation is something that music has but visual arts in general miss. There are further parallels of algorithmic notation with music. First, is not the author but the computer that executes the algorithm. Moreover, algorithm can be executed by different computers, using different operation systems, programmed in different software and presented by diverse output devices with various resolutions and other characteristics.

7. Algorithmic art

"Without the aid of a computer, it would not be possible to materialize quite so faithfully an image that previously existed only in the artist's mind. This may sound paradoxical, but the machine, which is thought to be cold and inhuman, can help to realize what is most subjective, unattainable, and profound in a human being" – Vera Molnar, algorithmic artist

We review here some of the key events in the history of computer generated art and present some of the best known authors from the field of algorithmic art.

First experiments with usage of computers in visual art were performed in late 1950th and early 1960th. More intensive development of algorithmic art began in early 1960th, and pioneers were two researchers in the area of computer graphics, Dr. A. Michael Noll from USA and Prof. Frieder Nake from Germany. Dr. Noll also wrote the first computer generated ballet in 1965.

In 1963 first computer art competition was held, sponsored by the U.S. journal "Computers and Automation". In 1965 first computer art exhibitions were held at Technische Hochschule in Stuttgart and at Howard Wise Gallery in New York. In 1971 Herbert Franke published the book "Computer Graphics - Computer Art" [6] in which he described the tools and principles of computer generated graphics, its artistic applications, history of computer art and its theoretical foundations. In 1976 Ruth Leavitt edited the book "The Computer in the Visual Arts" [8] which presented texts of three dozen of early computer artists like Vera Molnar, Manfred Mohr, Edward Zajec and Charles Csuri.

Several authors proposed the name "algorithmic art" and "algorists", and Benois Mandelbrot, mathematician who discovered fractals, also wrote that "… astonishingly complex and beautiful graphics can be generated by surprisingly plain algorithms. Hence the term *algorithmic art*, which I use at present" [4].

Some of the best known algorithmic artists we present here are Vera Molnar, Jean-Pierre Hébert, Roman Verostko and Manfred Mohr. What is particularly interesting is their background and how they approach algorithmic art.

Vera Molnar was born in Budapest, Hungary in 1924. She was a classical artist using geometric themes, and her aim was to create valuable works of art in a conscious way. In 1968 she began to use a computer to assist her. She started to create a series of abstract works generated from a procedure in which simple geometrical shapes and their combination were successively altered in small steps, and she wanted to find which alteration lead to the aesthetically most appealing result.

Jean-Pierre Hébert was born in Calais, France, in 1939. He is educated as a classic artist and he started to create digital conceptual algorithmic art in 1974, while in 1979 he engaged in intensive experimentations in creating plotter drawings with computers. His professional background in engineering and computer programming languages originally led to a consulting career, though he maintained his interests in arts and mathematics. In 1983 he moved to United States and ceased consulting to devote himself fully to art. Hébert is experimenting with various media from paper, glass and mirror to wood, steel, and sand. He is also working on digital video animations, computerized kinetic sculptures, and organic algorithmic drawing devices such as paint-dripping pendulums. In 2003 Hébert was appointed Artist in Residence at the Kavli Institute for Theoretical Physics at University of California at Santa Barbara.

Roman Verostko was born in Tarrs, Pennsylvania, in 1929. He was educated as artist and historian, but spent 16 years as a Benedictine monk. In the beginning of 1980th, after 30 years of work as a traditional visual artist, he started working with algorithmic graphics using classical pen plotter. He is one of the most original algorithmic artists, and besides a voluminous art production he also wrote a number of essays on algorithmic art and on his own methods of work. He is using the term *epigenetic* to describe the algorithmic procedures in his work, identifying the biological analogues for art works executed with algorithms created by artists. In his own words: "The epigenesis of organisms is the process whereby a mature life form grows from its seed. In this analogy the software may be viewed as genotype or the seed that contains all the information necessary for growing the mature form."

Manfred Mohr was born in Pforzheim, Germany, in 1938, He was educated as an artist, but he also used to play tenor-saxophone and oboe in a jazz group. In 1969 he made his first drawings with a computer. From early 1970ties he began his artistic work on a cube structure, and in 1977 he begins to work with the 4-D hypercube and graph theory. In late 1980ths he extends work to the 5-D and 6-D hypercube. In 1998, after using exclusively black and white colours for three decades, he starts using colours to show the complexity of the work through differentiation. In his own words: "What interests me, are the two-dimensional signs (graphics) and their visual ambiguity resulting from the projection of the lines of the cubes from higher dimensions into two-dimensions". Manfred Mohr received a number of international prizes for his work. Since 1981 he lives and works in New York.

8. Conclusions

One could possibly think that since algorithmic art is generated by a program, its author doesn't need to use any aesthetic judgments. However, as James Faure Walker argues in his book "Painting the Digital River" [14]: "… these artists make aesthetic decisions all the way through - how to start a drawing, what materials to use, how to decide when it is complete, and which drawings actually work". I might add to this that nothing can be created without the *initial idea* about the artwork. Besides, the author constantly *evaluates visual outputs* obtained during *experimentation* with the program and on the basis of this makes changes to the program until satisfactory visual results are obtained.

This also indicates a specific character of algorithmic art: the author has to possess *rational abilities* required to compose the algorithm and write the corresponding computer code correctly from both the syntactic and semantic point of view, but he also needs *intuitive and aesthetic abilities* required to select visually promising alternatives.

We have already discussed the potential for *experimentation* in algorithmic art as well as its importance in achieving good artistic results. Undoubtedly, experimentation is also present and important in a traditional art, but algorithmic art is using its full potential.

At the end I would like to recommend readers several of the most interesting and informative recently published books on computer art. Anne Morgan Spalter's book "The Computer in the Visual Arts" [11] is the first book devoted to detail description of principles and art applications of numerous technologies used in computer art like digital painting, electronic colour, printing, rendering, multimedia and Web.

James Faure Walker, classical artist who is also intensively working with computer art, in his quite informal book "Painting the Digital River» [14] gives a personal view on computer art. As a painter, critic and educator he analyses digital art culture and compares it with classical art. As already mentioned in this text, Bruce Wands in his book: "Art of the Digital Age» [15] gives a description of different forms of digital art and presents a number of examples of these forms.

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