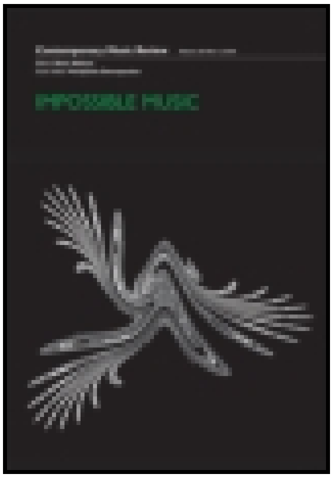

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Towards an "Automated Art": Algorithmic Processes in Xenakis' Compositions

Peter Hoffmann

A lifelong quest of Xenakis' artistic endeavors has been the creation of an ''automated art''. Examples are the use of Cellular Automata (CA) for the simulation of complex ''harmonic'' evolutions and his recent Dynamic Stochastic Synthesis program (GENDYN). The phenomenon of automated art is a challenge to present-day musicology. An adequate music analysis approach must be, to my belief, a computational (or procedural) one. The goal is to reconstruct the laboratory conditions of the algorithmic creation process, in order to unravel the multiple layers of complexity which in principle are not accessible from the study of a musical score or a sonagram. In this spirit, the author has simulated the CA model used by Xenakis in *Horos* (1986) and *Ata* (1987) and has recomputed Xenakis' electroacoustic composition *GENDY3* (1991).

KEYWORDS: Algorithmic composition, chaos, cellular automata, computational musicology, computer music, sound synthesis

We find ourselves in front of an attempt, as objective as possible, of creating an automated art, without any human interference except at the start, only in order to give the initial impulse and a few premises, like in the case of the Demiourgos in Plato's Politicos, or of Yahweh in the Old Testament, or even of Nothingness in the Big Bang Theory.

(Xenakis 1992: 295)

I. Introduction

Xenakis belongs to the pioneering generation of computer music. However, he practiced more than just "computer music." Xenakis is a major promoter, if not an inventor, of the radical idea of "automated art." Throughout his whole career, besides his activity as a "normal" composer, he invested considerable time and effort in creating, as it were, composing robots. With *GENDY3* (Xenakis 1991), Xenakis created a reference work of pure algorithmic composition, a music ''composed'' by the computer.

Automated score composition was mentioned for the first time by Xenakis as early as 1957 (Xenakis 1957[1]). Around the same time, he also put forward the idea of algorithmic sound synthesis (cf. Varga 1996: 42–44), much in advance of the French electroacoustic music scene at the time. Xenakis is also known to have preconceived granular synthesis (LePrince-Riguet 1981: 53, Xenakis 1992: xiii). But what is even more important is how Xenakis used the computer. His approach was to not use it as a tool for computing standard acoustical models,

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but rather as a self-sufficient automaton, which creates the acoustic shape of a whole composition. His ultimate goal was to enable the computer actually to carry out a compositional process. In one case, he used a cellular automaton to compute the notes (pitch/duration/timbre) of a score (''macro-composition''). In the case of GENDYN, composition is done on the level of the ''atom'' of digital sound, the sample (''micro-composition'').

Cellular automata (CA) have been employed in the past by a number of composers (cf. Chareyron 1990, Millen 1990, Hunt *et al.* 1991, Miranda 1993). They have been applied to score composition by Xenakis, who used CA to combine scales of durations and scales of pitch (''sieves'') in order to create complex temporal evolutions of orchestral clusters. His idea of using sieves for sound synthesis, dating from the beginning of the 1980s (Xenakis 1996: 149–150), seems not to have been tested. The creation of sieves as such, however, has been sufficiently formalized, and Xenakis' published listing of a sieve-generating computer program could serve as a core for computing ''sieved'' sound (Xenakis 1992: 277–288). If Xenakis had succeeded in using sieves for sound synthesis, he might also have thought of using CA in combination with them, similar to the way he combined these two formalisms in *Horos* (1986), for orchestra.

The GENDYN program, on the other hand, produces a macroscopic musical structure (pitch/duration/timbre) by means of microscopic sound synthesis (called ''Dynamic Stochastic Synthesis''; Xenakis 1992: 289–293). The geometric shape of the sound signal (the ''wave form'') is incessantly (de)formed by having its breakpoints perform independent stochastic random walks in both amplitude and temporal spacing between breakpoints. The resulting modulation of frequency and amplitude cover the ample field between stable pitched tones and complex modulation noise.

There is much debate about why and how Xenakis applied mathematical theories in his art. Some regard his collected writings in *Formalized Music* as a sort of cookbook for composition. I think this is an over-simplification. There is more to his project of ''art/science'' than just inventing new compositional techniques (cf. Eichert 1994, Hoffmann 1994). His theories of ''symbolic music,'' ''metamusic,'' etc., have a *raison d'être* of their own, quite apart from their acoustic results, which, by the way, are more than just exemplifications of composition theories. The scientific and intellectual background of Xenakis' music must be seen as an integral part of his work, in the sense of ''concept art.''

In what follows, I will describe the cellular automaton used in *Horos* and *Ata*, and how it is put to compositional work by Xenakis. I will then comment on common features with his other algorithmic composition procedure, ''stochastic synthesis.'' These descriptions will serve as preparation for a concluding discussion of Xenakis' idea of ''automated art,'' which today seems to me more topical than ever (cf. Huge Harry 1996).

II. Automation

In order to automate a task, it must be specified in a rigorous way, suitable for mechanical execution on a machine. On a computer, this specification is an algorithm. When fed a program, the computer simulates the automaton described by the program. When fed another program, the computer behaves like that automaton. This feature is called universality: a universal computer (i.e.

any of our programmable computers) is able to imitate any other conceivable automaton. Here we ignore all issues of human interaction other than providing the computer program itself, because Xenakis has been mainly interested in this kind of classical, self-contained automata.

Kristine Burns, in her dissertation on algorithmic composition, goes so far as to refer to almost all music written by Xenakis as ''algorithmic'' (Burns 1994: 64–69). In the present article, however, the word is used in much more strict a sense. ''Algorithmic'' music, according to this notion, is music that is computable, i.e. can be generated by a Turing Machine, an idealized thought model of a computer. This designation does not apply to most of Xenakis' composition procedures, where formal models are often employed in an informal way, and/or mixed with others. But CA and stochastic synthesis are indeed examples of a ''Turing'' music. This is because the algorithmic composition process can in theory be carried out anywhere at any time on any machine, and will always yield the same result. So it can also be carried out by a musicologist, who may add some more lines to the computer program in order to inspect and visualize the algorithmic activity of the program. This constitutes a ''procedural approach'' to music analysis: examining how a piece of art comes into being instead of only studying the end product (the score or recording) (cf. Laske 1988).

The very idea of automation is intimately linked to the logical foundation of mathematics and science as well as to the notions of axiomatic method and formal proof. Preconceived by the ancient Greeks, it was formulated by the mathematician David Hilbert as a challenge to the mathematical community around 1900. The mathematician Gregory Chaitin states the ''Hilbert problem'' in the following way:

> Hilbert's idea is the culmination of two thousand years of mathematical tradition going back to Euclid's axiomatic treatment of geometry, to Leibnitz's dream of a symbolic logic, and Russell and Whitehead's monumental *Principia Mathematica*. Hilbert wanted to formulate a formal axiomatic system which would encompass all of mathematics. . . . A formal axiomatic system is like a programming language. There's an alphabet and rules of grammar, in other words, a formal syntax. . . . Hilbert emphasized that the whole point of a formal axiomatic system is that there must be a mechanical procedure for checking whether a purported proof is correct or not. . . . In other words, there is an algorithm, a mechanical procedure, for generating one by one every theorem that can be demonstrated in a formal axiomatic system. . . . That's the notion that mathematical truth should be objective so that everyone can agree whether a proof follows the rules or not. (Chaitin 1997: 14–16)

The mathematician Allan Turing, answering Hilbert's challenge, devised in 1936 a formal system capable of doing what Hilbert had wanted – his famous ''Turing machine'' (cf. Gandy 1988). He also proved that it was inherently incomplete; not everything that is a true mathematical statement can be automatically computed: there are simply not enough conceivable Turing machines! The famous incompleteness theorem established by Kurt Gödel in 1931 is implied by Turing's findings. The Turing machine is a simplified thought model of a computer. Six years later, the first physical computer was constructed (cf. Rojas 1995). Today's computers are faster, smaller, and more comfortable to use, but in principle they are no more powerful than this first one, because all algorithmic action is bound to the specifications and limitations established by Gödel and Turing. Alonzo Church's ''Lambda Calculus,'' invented at the same time as Turing's machine, is an equivalent formalism equally expressing all the power and limitation of universal computation.

This short mathematical excursion is presented in order to point out the background of Xenakis' approach to automation in music. The use of CA by Xenakis provides one more evidence for this. It is almost certain that Xenakis found the automaton he ended up using in a scientific article dealing with the strength and limitation of universal computation in simulating physical reality (Wolfram 1984). Given his lifelong interest in computation issues, Xenakis' use of CA in *Horos* can therefore be understood as an implicit demonstration of the strength and limitation of universal computation in music composition.

III. Cellular Automata

Cellular automata are especially interesting in the context of automation, and that is probably why Xenakis paid tribute by applying them in some of his later compositions. Cellular automata demonstrate fundamental notions such as universal computation, chaos, and incompleteness in a graphical way. They also make tangible the fundamental equivalence between formal systems and dynamic systems, for they are both artificial dynamic systems and information processing machines (Casti 1995: 147). Xenakis' engagement with CA, therefore, reveals more than just the use of a mechanism to create complex cluster textures. Cellular automata allow for the study of both the universal features and the fundamental limitations of algorithmic action. Using CA for music composition therefore means, at least in the case of Xenakis, to reflect upon the nature of a machine music, i.e. about automated art.

A cellular automaton is digital in three ways. It evolves in discrete time steps, as if being driven by a "clock," as in a computer. Its space coordinates are discrete, too, as are the input and output of the automaton. A distinct point in space at a distinct point in time having a distinct value can thus be represented as a colored "cell." A CA with one space coordinate evolving in time therefore creates a rectangular grid of unit cells (figure 1). The value of each cell at a specific time point is determined as a function of its adjacent predecessor cells at

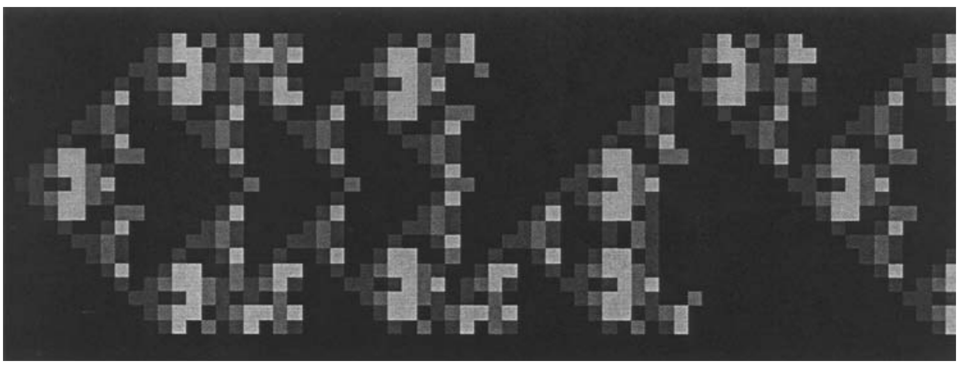

Figure 1
The evolution of the cellular automata in Horos, mm. 10–18.
Note: Time proceeds from left to right. Note the perturbation of its regular behavior at time slice 32, and the return to regularity at time slice 55 (equivalent to starting point).

the previous time point. This (recursive) function is called the rule of the automaton. Each rule defines a different automaton.

Cellular automata, being discrete dynamical systems, all exhibit one of three classes of dynamical behavior. The automata of the first class soon reach a stable state no matter what initial state they started from. They are governed by a "point attractor." In terms of hydrodynamics, one can speak of a "laminar flow." The second class comprises automata which, starting from arbitrary initial states, always evolve to small sets of periodic states. These correspond to "torus attractors." In terms of hydrodynamics, they represent "convection flows." The third class is made up of automata whose evolution is "chaotic." In contrast to the two previous classes, these automata are sensitively dependent on their starting conditions. They are characterized by "strange attractors," and, in terms of hydrodynamics, they represent "turbulent flow." Certain automata of a fourth class are capable of universal computation. The CA in *Horos* belongs to the third class and is governed by a rule which is capable of simulating diffusion processes, e.g. in liquids (see below). Xenakis explicitly named this property as a motivation for using CA dynamics in his music.[2]

In the composer's manuscript of *Horos*, there is a little arrow on the second quarter-note beat of measure 10, along with a vector of numbers (4200410), which turns out to be half of the rule of the automaton. The CA actually starts on the first quarter-note beat of that measure, with the central pitch D♭4 in the brass. The full rule is (2004104200410), as can be derived from the score. This string of numbers is the standard encoding of a CA rule as an "*n*-ary" number (5-ary, in this case). The number of digits indicates the argument range (the domain of the function), and the "arity" indicates the value range (the co-domain of the function). The rule is read from right to left as follows: argument 0 (first digit from right) is mapped to value 0, argument 1 (second digit from right) is mapped to value 1, argument 2 (third digit from right) is mapped to value 4, and so on. These values are assigned by Xenakis to orchestral timbres: value 1 is assigned to brass, value 2 to woodwinds, and value 4 to strings. (There is no value 3, and value 0 is assigned to silence.) The rule is a "totalistic" one, meaning that the value at time t is computed as the sum (the "total") of the values of itself and its two adjacent cells at time step t-1. A sum is a commutative mathematical operation, so the automaton shows lateral symmetry around its center pitch. The reader is invited to check figure 1 against the rule.

It is important to note that the CA used in *Horos* does not serve to determine pitch. Pitches are predetermined. They belong to a non-octaviating scale of twenty-three unevenly spaced pitches reaching from D2 to C6.[3] The sieve is dominated by Xenakis' well-known interlocked tetrachord configuration (e.g. F♯–B/G–C) which the composer attributes to Javanese music (Varga 1996: 144–145). This scale does not seem to be readily reducible to a closed sieve formula, contrary to the sieves usually demonstrated by Xenakis in his writings. The asymmetrical additive rhythm starting in measure 14 (after the uniform meter of m. 10; mm. 11–13 do not belong to the CA material) is similar in being reminiscent of a sieve structure, but more in a qualitative rather than a quantitative sense.

These scales of pitch and duration are not yet music, they cannot "sound" by themselves (according to Xenakis' terminology, they are "outside-time"). The CA serves to "play" them by pairing durations and pitches and assigning them to the timbral classes by virtue of its rule. In doing so, the automaton creates a typical pattern, the so-called "Sierpinski gasket." This self-similar fractal structure is made of triangular gaps (see figure 1). In *Horos*, each vertical slice of this pattern is represented as a pitch cluster. These clusters have an interesting internal structure. They are bounded by ascending and descending brass scales, and their "filling" consists of dense color-chords in woodwinds and strings. The aforementioned vertical symmetry of the CA is not obvious in the score: it is warped by the nonlinear spacing of the pitch intervals according to the sieve. It is as if a collection of tuned chimes were rung by a complex mechanism.

The spatial limitation to twenty-three pitches makes the automaton repeat itself after a succession of thirty-one iterations ("chords"). This fact can only be ascertained by simulation, it cannot be realized by a study of the score itself. Now, knowing the periodicity of the automaton, one can understand why Xenakis replaces the lower half of chord 32 with the lower half of chord 17: it is in order to avoid this repetition. His manipulation perturbs the CA's lateral symmetry for the following twenty-five chords. With chord 55, however, the automaton finds its way back to exactly the same configuration as that which had been "destroyed" before. In other words, the automaton is captured again by its periodic attractor. (Note that the CA as such has a strange attractor, but under spatial limitation, even a chaotic CA becomes periodic.) After eleven more chords, when the pitch-scale is sounding over its full ambitus, Xenakis stops the process.

This concludes the description of how Xenakis uses CA for his "macroscopic score synthesis." This description results from a close examination of the CA model underlying the score data, according to the procedural analytical approach. The procedural analysis also enables one to check for "errors" in the score. There are twenty pitches out of 550 which are not "in place" (roughly 3.6%). Given the rigid global character of the whole section, intentional changes by Xenakis can almost be ruled out. As a matter of fact, many of the pitches that do not fit into the automaton are obvious copying errors (change of key, wrong octave, a series of consecutive errors after having taken a pitch too high, etc).

One year later, in *Ata* (1987), Xenakis reused parts of the *Horos* automaton. He reproduced mm. 10, 14, 16, and 17 as mm. 126, 121, 130, and 128 of the new piece, while inverting three of them in time. He also faithfully reproduces the "errors" found in the *Horos* score. This indicates that he might have copied either directly from the score, or from an intermediate representation, and not from the CA model itself. The reversals of mm. 126, 121, and 128 are particularly interesting from a theoretical point of view. The CA rule used is an example of an irreversible time flow. It entails a loss of information: three predecessor values are mapped to a single successor value, so the rule is not reversible in time. When Xenakis declared that "indeed, much like a god, a composer may create the reversibility of the phenomena of masses, and apparently, invert Eddington's 'arrow of time'" (Xenakis 1992: 255), he could have been referring to an example like the retrograde of these automaton sequences, because they are discrete models of physical systems.

IV. Chaos, Emergence, Parallel Reciprocal Action

A distinct step in the compositional process as conceived by Iannis Xenakis consists, as we have seen in the case of the *Horos* automata, in establishing a temporal ordering on the points of a duration structure which itself is "outside" time. It is only through this temporal ordering that the direction of the musical evolution "inside" time – its "dynamic" behavior – is fixed. These dynamics, as far as automatic composition is concerned, cover the ample field between order and chaos. They can be represented as a discrete chain of transformations of system states: the succession of states $f(0)$, $f(1)$, $f(2)$ . . . $f(n)$ gives the temporal evolution of the piece. In both of Xenakis' algorithmic composition procedures, CA and dynamic stochastic synthesis (GENDYN), the state chain is defined by the general recursive scheme:

$$f(t) = g(f(t{-}1)).$$

The term "recursive" means that the determination of a state has recourse to the determination of previous states, which in turn take recourse to previous states, and so on. To avoid infinite regress into the "past," the recursive chain has to be "anchored" in an initial state $f(0)$. This initial state sets the very "beginning of time." In the *Horos* CA, this is a single brass sound, D♭4. The recursive state transformation is used to evolve cluster configurations in time according to a simple local rule, which yields complex output because of parallel, reciprocal action between the tone "cells." Each individual cluster configuration is derived from its predecessor state by applying the same local CA rule in parallel to all of its constituents. The recursive formula of a totalistic CA with range 1 has the following form:

$$f_i(t) = f_{i-1}(t{-}1) + f_i(t{-}1) + f_{i+1}(t{-}1),$$

where i is the spatial coordinate of a cell.

This rule is in fact nothing else than a discretization of the differential equation for diffusion processes in physics (cf. Hoffmann 1995: 3–5). Cellular automata are used by Xenakis as a means for "inside-time" composition: they are one solution to the problem of projecting structures "outside-time" (unordered sets of intervals or durations) into time.

In the case of GENDYN, the initial state is silence, i.e. a degenerated waveform with all its breakpoints set to zero amplitude. The recursive transformation is the parallel (de)formation of this waveform by stochastically deplacing its breakpoints, i.e. by acting on tiny segments of the physical sound signal. Each waveform comes about as a nonlinear stochastic variation of its predecessor. In other words, the amplitude values and the spacing of its breakpoints are computed as stochastic variations of the same breakpoints in the foregoing waveform. The recursive formula of GENDYN has the following form:

$$f(t) = f(t\text{-}n) + \text{random(t)},$$

where n is the number of breakpoints.

It is striking to note that in both cases where Xenakis relies on rigorous automata in composition, he makes use of parallel reciprocal action, chaos, and emergent processes. Cellular automata are classic examples for the study of these phenomena (cf. Wolfram 1994). For GENDYN, this is less obvious, and has not been explicitly put forward by the composer himself nor by his research colleague at the Centre d'Etudes de Mathématique et Automatique Musicales (CEMAMu) (cf. Xenakis 1992, Serra 1993). Yet, sonic self-organization of the sounding matter is indeed the most prominent feature of stochastic synthesis. It is not the Law of Large Numbers that governs the sonic behavior of GENDYN but the amplification and cumulation of chaotic probability fluctuations through random walks. The result is not a statistical average but, on the contrary, a tendency toward extremes (cf. Feller 1968). Pairs of reflecting barriers (which are part of the mathematical random-walk model) help auto-organize these tendencies into more or less stable states. This observation has been made through extensive simulation of the GENDYN synthesis procedure according to the procedural analytical approach.

The acoustic result of the GENDYN synthesis process is a chaotic mapping of pitch and duration, somewhat similar to that of the *Horos* automata. Like a CA, GENDYN is driven by a deterministic rule: the random term of its formula represents in fact the deterministic simulation of randomness on a computer (it is a "chaos generator"). For specific settings of the random-walk positions and number of wave breakpoints, specific patterns of discrete, finite pitch sets (i.e. scales) emerge, created by combinatorial permutation of minimum and maximum spacings between the waveform's breakpoints (i.e. the length of the waveform segments between breakpoints). The macroscopic duration of these pitches is equal to the time interval during which a specific permutation remains relatively stable (an "attractor" of the dynamic stochastic synthesis system). Figure 2 shows a graphical plot of such a pitch curve over time.

From this analysis, a systematic ordering can be established listing the various possible scales available to GENDYN synthesis, similar in completeness to that of the theory underlying Xenakis' sieves (cf. Hoffmann 2003). GENDYN scales, too, are non-octaviating, and they reach over the whole audible spectrum. It is very interesting to see how Xenakis created one of his most typical stylistic features (non-octaviating scales) in sound synthesis, which seems completely alien to macroscopic pitch composition. Even if this was not originally intended, with stochastic synthesis, through its self-organizing properties, Xenakis reproduced a feature of his own macroscopic musical language.

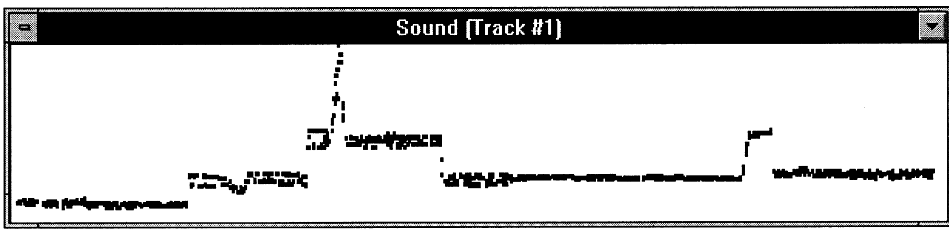

Figure 2
The emergence of scales in GENDY3.
Note: Time is represented along the horizontal axis, and frequency along the vertical axis. Note the relative stability of three main pitch "attractors," and the small variations with casual "slips" towards the high register; also how the pitch movement sometimes seems to split into two parallel "voices."

V. Conclusion

We have seen that formal systems, once the dream of mathematicians to solve any conceivable mathematical problem objectively, once and for all, are limited in their expressivity. They are not capable of formalizing the whole of mathematics. Provable facts form a proper subset of mathematical truth. The weakness of formal systems is, at the same time, a strength: since they solely rely on mechanical manipulation of ''meaningless'' symbols, they offer themselves to automation. In fact, a computer program is nothing more than the ''animation'' of a formal mathematical proof. An input (state) is transformed into an output (state) through a succession of finite steps, each performing a well-defined operation.

The incompleteness of formal systems is reflected in algorithmic action by the fact that the halting problem cannot be algorithmically decided. This means that there exist well-defined problems that are not computable. In fact, formulated from the perspective of number theory, the majority of numbers are non-computable, i.e. the majority of numbers cannot be described by a finite algorithm. The same holds for music because its representation as a sample stream can be conceived as (the decimal expansion of) a number.

Computable solutions form a proper subset of the problems that can be formally specified. This leads to an equivalent information theory statement which says that no program can calculate a string more complex than itself (cf. Chaitin 1975). Applied to the notion of scientific theories, this means that there are aspects of reality that cannot be reduced to closed formulae and general explanation. Scientific theories are a proper subset of physical reality. Much of reality is irreducible in this sense, and can therefore only be studied through explicit simulation and empirical observation. One example are cellular automata: some of them are capable of universal computation. Universal computers can only be simulated by other universal computers. This amounts to saying that nothing can better compute such a cellular automaton than itself.

Chaos seems to play a significant role in this, as evoked by a member of the Santa Fe Insitute for Complexitiy Studies. Chaos provides a certain loophole to algorithmic incompleteness:

> A world without strange attractors and, hence, without chaos would be very impoverished in the number of mathematical theorems that could be proved. This conclusion, in turn, implies that whatever real-world truths might exist, the overwhelming majority of them cannot be the counterparts of theorems in any formal logical system. Of course from this perspective we might already be living in such a world. But the existence of strange attractors allows us to hold out the hope that the gap between proof and truth can at least be narrowed – even if it can never be completely closed. (Casti 1995: 148–149)

What does this evocation of chaos and strange attractors imply for Xenakis' concept of automated art? This concept is certainly not the dream of an ''artificial artist.'' An automaton cannot ''create'' in the artistic sense of the word. This is implied by Gödel's, Turing's, and Church's findings, and is explicitly recognized by Xenakis.[4] Automated art, in the composer's view, uses the processing power of a computer to extrapolate the ramifications of artistic thought, all the while reserving for the human the role of creative decision making. The computer, for Xenakis, is neither just a tool for computer-aided composition nor a wonder-machine for the realization of an artificial new cyber-art. It serves as a powerful instrument for the artistic verification of fundamental compositional ideas. In the case of CA, the idea relates to the complex temporal evolution of dense orchestral clusters, typical of his late instrumental style. In the case of stochastic synthesis, the idea is nonlinear wave shaping in order to create unheard-of sonic evolutions beyond any established acoustical theory. In both cases, Xenakis exploits the structural richness and emergent properties of chaotic processes.

The "automation" of creative action is a natural consequence of the attempt to formalize musical thought. But automated art cannot be a substitute for human creativity. Its true value is only revealed when it is harnessed by human creativity. Its rich potential serves to stimulate and challenge artistic invention as well as to confront the listener (and, in the first place, the composer himself) with a different acoustic reality. Therefore, it is not only legitimate but important to break the rules and to change the specifications wherever it seems appropriate in order not to be trapped by machine logic. This is, I think, the lesson that can be learned from Xenakis' project of automated art.

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Notes

1. Partly reprinted in Xenakis (1992: 25, 37).
2. "Cellular Automata . . . are very simple rules which can create structures on very large surfaces. It is related to the nature of fluids, for instance. For me, the sound is a kind of fluid in time, that is what has given me the idea to transfer one area to the other. I was also attracted by the simplicity of it: it is a repetitious, a dynamic procedure which can create a very wealthy output. . . . Bars 10 and 16 [of *Horos*], for instance, are areas created in this way" (Varga 1996: 182, 200).
3. "Scales of pitch (sieves) automatically establish a kind of global musical style, a sort of macroscopic 'synthesis' of musical works. . . . We can obtain very rich simultaneities (chords) or linear successions which revive and generalize tonal, modal or serial aspects. It is on this basis of sieves that cellular automata can be useful in harmonic progressions which create new and rich timbric fusions with orchestral instruments. Examples of this can be found in works of mine such as *Ata*, *Horos*, etc." (Xenakis 1992: xii).
4. "The computer, which has arisen through the wealth of achievements of the human mind through the millennia, cannot create anything new. Several mathematicians, for instance the Nobel prize-winner Simon Newell, tried to create theorems with the computer. Recently it was demonstrated that this is not possible. . . . Beneath the level of consciousness there lies all this fantastic amount of intuition that ultimately leads to a rational expression, but without this intuition it is impossible to create anything" (Xenakis 1996: 148–149).