STOCHASTICS AND GRANULAR SOUND IN XENAKIS' ELECTROACOUSTIC MUSIC ([1])

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ABSTRACT

In some of his early electroacoustic pieces, Xenakis pursued ground-breaking explorations in territories that, in retrospect, appear quintessential to his work in general. If we consider those electroacoustic works alongside with orchestra music like *Pithoprakta* (1955-56) and *Achorripsis* (1956-57), we get a composite picture where the theory of "stochastic music" is often managed in conjunction with a theory of sound in terms of "sonic quanta". After all, Xenakis' first proposal as to the *granular* nature of sound is found in a paper on *stochastic* music (written in 1959). We can argue that the laws of stochastics and a kind of quantum-oriented understanding of sound were somehow closely connected in Xenakis' mind. In this paper I discuss and try to characterize that connection.

1. INTRODUCTION

In the late 1950s, Xenakis' compositional approach was mediated by a variety of historically specific factors as well as by personal experiences and ideology concerning sound and music. Of special relevance are early electroacoustic works like *Diamorphoses* (1957), *Concret PH* (1958) and *Analogique B* (the tape part of *Analogique A et B*, for nine strings and tape, 1958-59). If we consider such works alongside with earlier orchestral scores like *Pithoprakta* (1955-56) and *Achorripsis* (1956-57), we get a broader picture where the theory of "stochastic music" is often managed in conjunction with a view of sound in terms of short sonic droplets, or "acoustical quanta". Solomos (2006) observes: « Xenakis expounds the *granular* paradigm as a "basic hypothesis (lemma)" … in the first part of the article "Elements of *Stochastic Music*", published in 1960 (finished in 1959) » (empahsis mine). There is reason to argue that, in Xenakis' mind, probabilistic laws were strictly connected with a quantum-oriented understanding of sound.

In the following I'll address that connection. I consider it of relevance in the history of music because it shows a highly significant tie between abstraction and formalisation (pioneering work in algorithmic composition) and empirical, even violent explorations in sound materials. The question is asked whether it was Xenakis' familiarity with stochastic formalisatoins that led him to a quantum view of sound or, *viceversa*, it was a special ear for granular sonorities that led him to stochastics. Indeed, a sense of

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[1] The first draft of the present paper was prepared in 2006, and it is reproduced here essentially unrevised, except for minor corrections and some editorial amendments.

granularity, an internal discontinuity and roughness, is peculiar to many xenakian sonorities across different musical resources – a kind of tactile, porous, fragmented quality of his "sound masses", a vapour-like or firework-like element in his "sound clouds". Xenakis' instrumental and vocal music after the early 1960s branched into a variety of developments only indirectly related to stochastics. However, some of his later electroacoustic and computer-generated works are still related to stochastic methods. We can probably claim that electroacoustics and the computer represented for Xenakis a specially fit medium in order to explore granular sound materials by means of formalised stochastic procedures.

2. THE WAY TO STOCHASTIC MUSIC (MOTIVATIONS)

In 1955 a short essay of the young Greek immigrant appeared, *The Crisis of Serial Music*. Xenakis' reaction to the then blooming musical serialism, whose Parisian champions included the elder René Leibowitz and the younger Pierre Boulez, had been first one of curiosity (witness is the serially-organised section of *Metastaseis*). Yet it became very soon one of well-argumented criticism. Xenakis viewed the principles of rigourous serial composition as a particular instance of combinatorial calculus, resulting mostly into sonic structures that human perception could only grasp statistically. That way – argued Xenakis – the linear polyphony that serialism was born of, in actuality collapsed because of the sheer complexity achieved. Therefore, one should better replace that pseudo-deterministic method within the calculus of probabilities, and resort to methods more consistent with perceptual phenomena of statistical profile. Other European composers held similar critical views of serialism (including György Ligeti and Franco Evangelisti).[2] Each composer responded in his own way to that state of affairs. Xenakis' response was stochastic music. He coined the term in 1956, while composing *Pithoprakta* (for string orchestra), when « the laws of the calculus of probability entered composition through musical necessity » (Xenakis, 1992: 8).

Furthermore, it is reasonable to assume that the heavy emphasis Xenakis put on formalised music in general and stochastic music in particular was also a question of tactics: a way for him to speak loud, so to say, and distinguish himself in the context of the European post-War avantgarde music. He could profit from his engineering background (before the war he was a student in the Polytechnique) in order to shape his personal profile in that cultural context.

Let's recall, too, that Xenakis' personal history at that point was already quite rich in experiences that had forged not only peculiar inclinations but strong auditory imaginations too: in his younger years, he had a fascination for the sound of rain and hailstorms, the cicadas in the fields singing in hundreds and thousands, and other natural events.[3] He had heard the guerrilla gunfires and the chaos of crowds protesting in the streets. In his early years in Paris, Xenakis went through an experience that we could call one of *ecoute reduit* (reduced listening *avant la lettre*): he tried to isolate the purely sonic element in those auditory

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[2] It is interesting to observe that the arguments of Ligeti and Evangelisti against radical serialism was mentioned by Adorno as a confirmation of his own criticism, in the Preface to the 1966 edition of his *Philosophie der neuen Musik*.

[3] Xenakis worked with earthquake sounds in *Diamorphoses*. For the orchestra composition *Terretekthor* (1965-66), he imagined that the listener is sitting on a rock in the midst of violent seafloods and winds, maybe under a thunderstorm, subjugated by the elements reaching her/him from all sides at random.

memories, from the semantic one. He started asking: « What is the structure of such kind of sound events, and their transformation in time? ». (Xenakis, 2003: 64) [4] Experiences initially loaded with an emotional charge, were now revived in order to abstract the laws of their dynamical structure, void of referential content – true *objects sonores*, in a way. Xenakis realized that such sound events could be musically shaped by procedures leaning on the laws of probability.

Xenakis' notion of "sound cloud" was born at the time. It was less an impressionistic metaphor, a poetic image, and more an operational notion, something that could be empirically implemented as a practical procedure, as an algorithm (Di Scipio, 2003). It was not a question of painting an auditory picture, but rather of empirically governing masses of sonic droplets or molecules, moving randomly – if observed from close – but having an average orientation and an overall shape – if observed from a distance (notice, here again, this element of "distancing", of abstracting). Xenakis made the analogy that his music would *work* the in much the *same way* a gas or cloud would.

3. STOCHASTICS (SOME DEFINITIONS)

A stochastic system or process, $x(t)$, is a family of monoparametric aleatoric variables. An aleatoric variable is a variable that can assume any value in a given range Ω, but conditioned by a given probability for each particular value in the range. A general notation is, then, $x(t;\ \omega)$, with $\omega \in \Omega$. A sequence of probability distribution functions, written $\sigma(\alpha_1,\ t_1;\ \alpha_2,\ t_2;\dots\ \alpha_n,\ t_n)$, is linked to the system states $x(t_1), x(t_2), \dots x(t_n)$ by corresponding probability measures:

$\sigma(\alpha_1, t_1; \alpha_2, t_2;\dots \alpha_n, t_n) = P\{ x(t_1) < \alpha_1,\ x(t_2) < \alpha_2,\ \dots x(t_n) < \alpha_n \}.$

A distribution function describes the profile of conditional probabilities for all values in the range Ω.

The word "stochastic" means that the process proceeds asymptotically towards a stable state, a destination (στοχος).[5] The process is defined as "ergodic" meaning that all sequences of system states are, although different in their details, statistically equivalent – they have the same spectrum. A stochastic process is precisely determined when all the probability functions linked to its states are precisely determined. That is virtually the case with passages of *Pithoprakta* (1956) and with *Achorripsis* (1956-57), two compositions of "free stochastic music" (see Chapter I in Xenakis' *Formalized Music*).

3.1 Free Stochastic Music

The adjective "free" means that the probability distribution S_n linked to the present state in the process $x(n)$ does not depend on distribution S_{n-1} linked to $x(n-1)$:

$P\{ x(1)= S_1, x(2)= S_2, \dots, x(n)= S_n,\}$

In that sense, such a process is "memoryless", it follows an « aleatory law without memory » (Xenakis, 1992: 23). Some passages of *Diamorphoses* represent the earliest studio applications of free stochastics.

[4] from a lecture delivered in 1980. Original text in French. Translation mine.

[5] I following here various sources including (Rota & Kung, 1980) and (Kac, 1984).

For a section in that piece, Xenakis utilised probability distribution functions to create thicker strands of (seemingly electronically generated) glissando sounds. He tried to achieve dense sound textures made of separate, discontinuos elements. In other words, here *sound* is understood as the overall Gestalt created by numerous overlapping smaller units.

In practical studio work, the approach raised serious technical questions. In addition it raised questions concerning the perception of the "density" in sound. At the time, density was a rather new dimension that a number of composers were dealing with. Density means, here, "sound events per time unit". Or, with Xenakis' terminology relative to his work for *Analogique A et B*, « grains per unit of volume » (Xenakis, 1992: 52). The assumption was that the individual sound particles are not equally spaced in time, nor otherwise regularly patterned, but randomly scattered (a periodic pattern would be an exception, a singular case in a larger field of possibilities). This notion of density is in fact related to time, representing the average number of elements spread across a time window. Others were concerned with spectral density, instead – i.e. the way that energy is spread in the frequency domain, as opposed to the time domain: think of the clusters of sine tone, combinatorially governed, in Stockhausen's *Studie II* (1953-54).

Apparently no research had ever been done on the auditory perception of density. Xenakis had to tackle the issue for himself, in order to determine degrees of density to be managed for compositional purposes. With empirical experiments and very basic studio procedures (layering of sound tracks), his attention eventually focused on a « logarithmic scale [with] base between 2 or 3 » (Xenakis, 1963: 69; Xenakis, 1992: 373). That means, one perceives a distinct increase in the thickness of a sound texture when the amount of individual events gets more-than-doubled or even tripled. Density was worked out roughly in these terms not only in the stochastic section of *Diamorphoses*, but also in *Concret PH*. The approach was to be pursued again in *Analogique A et B*[6].

3.2 Markovian Stochastic Music

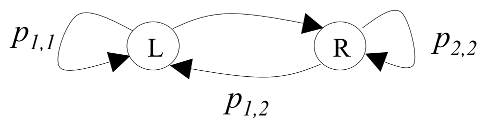
Different from the memoryless processes of free stochastic music, "markovian stochastics" require some process memory. That can be notated:

$P(S_{i,1})P(S_{i,1} \mid S_{i,2})\, P(S_{i,2} \mid S_{i,3}) \ldots P(S_{i,n-1} \mid S_{i,n})$

where $P(S_{i,1})$ represents any initial probability distribution function, and $P(S_i \mid S_j) = p_{i,j}$ is the probability that another specific distribution will come next (clearly, $p_{i,j} \geq 0$ and $\sum_{j=1}^{n} p_{i,j} = 1$). The simplest markovian process features a single memory cell: the next probability distribution is made dependent on (a function of) the current one.

For example, let's call L and R any two events or symbols determined by a markovian process, their sequence can be represented graphically like this:

$p_{2,1}$



or it can be represented as a bidimensional vector, called "transition probability matrix":

	L	R
L	$p_{1,1}$	$p_{1,2}$
R	$p_{2,1}$	$p_{2,2}$

Both in the graph and the matrix, $p_{1,1}$ is the probability that an L event or symbol is followed by another L event or symbol – in other words, it is the probability that the transition L → L will happen. Similarly, $p_{1,2}$ is the probability for transition R → L, $p_{2,1}$ is the probability for L → R, and $p_{2,2}$ is the probability for L → R. Let's consider the simplest case:

	L	R
L	0.5	0.5
R	0.5	0.5

A drunk person is very unlikely to walk straight, and at each next step s/he rather swings either to the left or to the right. At each new step, there's a 50% of chances that s/he moves to the left and a 50% of chances that s/he moves to the right: this is independent of the direction taken with the previous step – so that particular random walk is actually a free stochastic process. But suppose, now, that before leaving the pub for the street, our drunkard was painfully kicked in the left leg by a drinkmate. S/he will proceed in a different manner. The matrix should be rewritten, maybe like this:

	L	R
L	0.1	0.4
R	0.9	0.6

If the previous step was to the right, there's a 60% of chances that next will be to the right again, and a 40% of chances that it will be to the left. If, on the contrary, the previous step was to the left, there's a 90% of chances that next will be to the right, and a 10% of chances that it will be to the left again. Because of the pain in the left leg, two subsequent steps to the left are unlikely to occur. The drunkard will proceed randomly, but overall s/he will move more to the right (until some external event or obstacle causes her/him to take a different direction). Xenakis utilized markovian stochastic processes for *Analogique A et B*, though not in such a simple way.[7]

Markovian processes can have more than a single memory cell, such that probabilities at any given stage in the process, *x(t)*, depend on probabilities at stages, say, *x(t-1)* and *x(t-2)* – or any other two preceding states.

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[6] In a later interview, Xenakis said that the log base for his density scale was precisely 3 (Varga, 1996: 111). That matches exactly the values he calculated for *Analogique A et B*. Based on analytical data, however, I find no evidence that Xenakis actually managed density in this way, in *Analogique A et B*. The data shows that deviations from calculated values are quite frequent (Di Scipio, 2006).

[7] See (Xenakis, 1992: Chapter II and Chapter III), and discussion in (Di Scipio, 2006).

That would be represented as a more complicated graph, or as a tridimensional vector. In general, a Markovian process with *n* memory cells is captured in a *n+1*dimensional matrix.[8]

3.3 Xenakis' Sources for Markovian Stochastics (Music as Language?)

Xenakis' familiarity with the mathematics of stochatic systems was most probably based on a book written by a French authority in the field, Maurice Frechet (1878-1973). The book was titled *Methods des fonctions arbitraires*, and dated from 1938 (Xenakis, 1963: 97; Xenakis, 1992: 79).[9] It must be noted that, having read Frechet, Xenakis was ready to approach Information Theory with an awareness that all of it was fundamentally grounded into physics and more particularly into thermodynamics (Xenakis, 1992: 61).[10]

Markov chains were not just mathematical abstractions, but they were tools of use in physics, astronomy and chemistry (applications appeared even in psychology). In actuality, in 1913 the Russian Andrej Markov had shown that chain processes of the kind could model the statistical occurence of vowels and consonants in a given text – his example was Puškin's poem *Evgenij Onegin* (Kac, 1984). Studies in the statistics of natural languages bloomed in the 1920s and 1930s, and the perspective re-surfaced in Shannon and Weaver's famous *The Mathematical Theory of Communication* (1949). Shannon likened any human language to a « discrete-time information source » (Shannon & Weaver, 1949: 42), a mechanism generating strings of symbols (either letters or syllables or entire words). He asked what chances (probabilities) are there that, given any symbol *x*, symbol *y* will follow. In Shannon's words a physical system or a « mathematical model of a system generating such a sequence of symbols governed by probability values, is called a stochastic process » (Shannon & Weaver, 1949: 43). Now, that is actually a good definition for the approach Xenakis took in *Analogique A et B*, which indeed consisted in a mathematical model of an (imaginary) physical system that behaves « analogue to a stochastic process » (Xenakis, 1992: 81).

Xenakis came to know Shannon's book (where, by the way, references are made to the Frechet book he was acquainted with) (Shannon & Weaver, 1949: 49 and 51) probably thanks to Abraham Moles, active at the GRM in those years, author of the book *Theorie de l'information et perception esthetique* (1958). Xenakis might have known Moles already in Gravesano, before entering the GRM. As it was, Xenakis took Shannon's notion of discrete-time information source *a la lettre*: a strong similarity can be seen between his

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[8] Xenakis did not investigate that possibility. In the late 1950s, multidimensional transition probability matrices were being used for muiscal purposes by Hiller and Isaacson (1959). In the first edition of *Musique Formelles* (1963), Hiller's book is listed among the bibliographical references (Xenakis, 1963: 226). A tutorial on transition probability matrices for computer music composition can be found in (Dodge & Jerse, 1985: 283-288).

[9] The subtitle of Frechet's book must also be mentioned here: *Theorie des événements en chaine dans le cas d'un nombre fini d'états possibles*. It refers to "finite state space" and "discrete-time" Markovian processes, also known as "Markov chains" (Kac, 1984: 175a). That's the kind of Markovian processes Xenakis utilized in *Analogique A et B*.

[10] Frechet's book discussed many issues of interest for Xenakis, particularly including the definition of stochastic processes as "ergodic". The same definition is in Shannon's book, where it is discussed next to Markov chains (Shannon & Weaver, 1949: 50). However, Xenakis' reference on this particular subject is Frechet, not Shannon (Xenakis, 1963: 56 and 67). The composer later recalled: « I took the definition [of ergodic process] from the book of that important French mathematician, Maurice Frechet, who has written on Markov chains » (Xenakis, 1989: 53).

description of a stochastic system (Chapitre II of *Musique Formelles*) and the examples illustrated by Shannon (Shannon & Weaver, 1949: 42; Shannon, 1948). The output of his compositional "mechanism" (his word) was presented as strings of letters or "protocols" (Xenakis, 1992: 97-98) quite resemblant of Shannon's own examples with language. In fact, Moles' book has examples illustrated with sequences of letters and French words, but the similarity of Xenakis' protocols to the Shannon's strings of letters seems (to me) stronger. I can add that, in *Musiques Formelles*, Xenakis discussed such a general point as the calculation of entropy in terms of probability and bits of information very much resembling Shannon's own discussion of the same subject (there he seems to literally follow or even rephrase Shannon).

In a 1989 interview (Varga, 1996: 82), the composer commented again on the idea that an imaginary language could be built upon weighted probabilities assigned to a set of basic symbols, and indeed attributed the idea to Shannon (this is of course incorrect from a rigorous historical perspective, but it makes sense in the context we are examining). In the particular circumstance, Xenakis mentioned Noam Chomsky's confutation of the idea that artificial languages can work the way natural languages can, but he also added: « music is not a language ». In sum, the effort of stochastic music is *not* based on any presumed resemblance between music and language. In the following, I will claim that it was based on a particular notion of what the matter of music is, i.e. on a particular view of sound.

4. FROM STOCHASTIC MUSIC TO STOCHASTIC SOUND

Xenakis suggested that « stochastics is valuable not only in instrumental music, but also in electromagnetic music » (Xenakis, 1992: 43), where it may serve to shape « new sonic materials » and to develop them into « new musical forms » (Xenakis, 1992: 43). In my view, that statement implies a strong relationship between *music* structure and *sound* structure. The electroacoustic studio provided Xenakis with the technical opportunity to experiment a bridging of micro-structure (sound) and macro-structure (musical articulation).

Most of Xenakis' electroacoustic music has a textural kind of quality and offers a kind of tangible and porous acoustical surface. The splinters of burning charcoal, in *Concret PH*, provide a prototypical example. Atoms of electronically generated sine tones constitute the only material for *Analogique B*. Such works only consist in "sound clouds" with variable degrees of statistical order. Of course, sonorities of the kind are not at all stranger in the composer's instrumental works. As early as 1956, discussing free stochastic music as in *Pithoprakta*, Xenakis used terms such as « punktuell-granulierten Tönen » (and its variant « granuliert-punktuellen Tönen ») – meaning "point-like sounds" (referring to textures of string *pizzicati*, *frappé*, etc.) as opposed to sustained, « continuous sound » (Xenakis, 1956: 30 and 33; Xenakis, 1992: 12 and 16).

4.1 THE WAY TO GRANULAR SOUND

Spread across several of his writings are bits and pieces of an essay Xenakis has never actually written, whose imaginary title could be *The Crisis of the Fourier Analysis of Sound* – a perfect companion to *The*

Crisis of Serial Music. In the harmonic paradigm of Fourier analysis, all sound is an integration of a large number (ideally an infinite number) of circular functions (sine and cosine).[11] The composer often argued against that idea, and spoke of the « *impasse* of harmonic analysis » (Xenakis, 1992: 243). Fourier analysis represented for him a modeling tool of too poor use *vis a vis* the richness of actual sounds, including the sound of musical instruments and natural events. Likewise, Fourier was for Xenakis a wrong basis for sound synthesis: he rejected electronically generated mixtures of sine tones, like in the early works produced in the Cologne studio, or like in early experiments in computer music. Sounds synthesized with Fourier-based additive method were for Xenakis dull and lacking internal life, all too distant from the dynamical structure of interesting sonorities.

The twofold criticism – of Fourier analysis and of related synthesis methods – can be summerized in these terms: interesting sounds usually are non-periodic signals, and non-periodic signals can only represent limit-cases in the context of Fourier theory, where infinitely many circular functions are piled-up to approximate non-periodic behaviour. Xenakis' reaction to that state of affairs was, let's rather start from a situation of molecular disorder (noise) and eventually introduce degrees of order among molecules. To do that, we need an altogether different representation of sound, replacing timeless circular functions with time-finite functions. Sound would be then decomposed into tiny acoustical atoms. Large amounts of such atoms would be required for a variety of lively, internally rich sound materials, ideally ranging from noise to periodicity.

Let's recall Xenakis' famous "basic hypothesis": « All sounds represent an integration of corpuscles [grains], of elementary acoustic particles, of sound quanta. Each of these elementary particles possesses a double nature: the frequency and the intensity (the life-time of each corpuscle being minimum and invariable) [Each of these elementary grains has a threefold nature: duration, frequency, and intensity] ». (1960; in squared brackets is Xenakis' own re-rephrasing, in 1992) (Xenakis, 1992: 43). All sound is « an assemblage of a large number of elementary grains adequately disposed in time » (Xenakis, 1992: 43).[12]

Some observations:

● sound is described as a particular arrangement of a number of such particles (their frequency, intensity, duration and time position), so "duration" (length of the kernel functions) is included in the representation: the basic units sound is made of are not infinite circular functions, but time-limited functions, precisely located in time. In a task of sound synthesis, one would need to "dispose" them, to arrange them on the time axis.

● of crucial relevance is the density of the basic units;

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[11] This view was handed down along the decades after Jean-Baptiste Fourier's "analytical theory of heat" (described in 1807, published in 1822). Through numerous scientists and researchers (among them Georg Ohm and Hermann von Helmoltz, in the second half of the 19th century), the Fourier expansion series became *de facto* the standard analytical view of sound and mechanical acoustics in general, ultimately providing the modern harmonic paradigm of sound. One century earlier, the modern harmonic paradigm of music had also been consolidated, as in Jean-Philippe Rameau's *Traité de l'Harmonie* (1722). (Neither should be confused with the ancient Pythagorean harmonic theory).

[12] Xenakis spoke of "hecatombs of grains", too. The term "hecatomb" has today the semantic connotation of "incredibly many", or perhaps "innumerable". But the ancient Greek meaning is just "hundreds".

● the potential is opened up for a music where the macro-level structure and the micro-level structure can be shaped by means of similar rules. Music and sound can be articulated by virtually one and the same compositional process.

To make things easier, working on *Analogique B* Xenakis considered the grain duration to be fixed (« about 0.04 sec. » long) (Xenakis, 1960: 99; Xenakis, 1992: 54), and the distribution of grains in time unit to follow a uniform distribution function (in *Analogique B*, the time unit is 0.5"). What remained to be determined was the grain frequency, the grain intensity and the grain density. Driving the latter with Markov chains, Xenakis hoped to create « sonic perturbations » of a kind « unimaginable until now » (Xenakis, 1992: 47). Notions like "sound cloud" and "sound mass" could now receive a theoretical foundation and a practical implementation.

I must emphasize that such a reformulation of *sound* was advanced by Xenakis not as a separate theoretical formulation, but as a way of reasoning integral to a reformulation of *music* composition. It's like for Xenakis it seemed only consequential that the composition of sound should be done with markovian stochastics. In fact, *Analogique A et B* – his most thoroughly-going formalised effort before the computer age – proceeded hand-in-hand with a novel concept of sound. This must be considered, in my view, an incredibly seminal achievement, and one having less to do with aesthetics, and more with epistemology (not without consequences in musical aesthetics, of course).

4.2 GRANULAR SOUND (SOME DEFINITIONS)

How did Xenakis come to put forth his hypothesis[13] of the granular notion of sound and related formalisms? Did he put forth the idea as a way to generalize his approach of stochastic music, extending his music theory to cover sound too? Or was it rather the other way round, a genuine interest in complex sonic materials that led him to stochastics – first in music (with known instrumental resources) then in sound (with yet-unknown studio means)? Nobody can really say, but sure granular sound and stochastics seem to go hand in hand in Xenakis' work between 1955 and 1959 (and even later, as we shall see below).

The composer was aware that developments in the scientific representation of sound had occurred not long before he approached the subject. He knew the proposals advanced by the Hungarian-born British scientist Dennis Gabor in the late 1940s (Gabor, 1947).[14] In Xenakis' own words, the hypothesis of the granular

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[13] In the first edition of *Musique Formelles* (1963), Xenakis had used the French word "image", not "hypothése" (the 1992 English translation has "hypothesis"). His « description de la structure élémentaire des signaux sonores » was a starting point for musical work, « une image plutôt qu'un fait scientifiquement fondé » (Xenakis, 1963: 61). In the very first English translation (1960) we find the term « intuitive representation » (Xenakis, 1960: 86).

[14] Gabor's paper *Acoustical Quanta and the Theory of Hearing* described a quantum representation of sound that later became crucial to research and musical applications of "granular synthesis". See (Di Scipio, 1998) for the reception of Gabor's theory in musical and scientific circles, and (Roads, 2001) for an overview of many "microsound" developments. A historical precedent to the quantum notion of sound is in the corpuscular mechanicism of 17th century scientists, notably in the work of Isaac Beeckman and Daniel Gassendi. We may also – but perhaps all too easily – connect "quantum" and "corpuscolarism" to ancient "atomism", as in Democritus and other pre-Socratic *physicoi* (philosophers of nature). An erudite scholar has recently linked Democritus' atomism back to Anaximander's cosmogonic principle of *apeiron*, usually understood as "the infinite" or "the indefinite", but more precisely (from Akkadic and Sumeric roots) "dust: innumerable particles of matter, of which Earth is made" (Semerano, 2005; translation mine).

structure of sound was « a first approximation [of the proposals] introduced in Information Theory by Gabor. In the so-called Gabor matrix, a sonic event is resolved into elementary acoustic signals of very short effective durations, whose amplitude can be divided equally into quanta in the sense of information theory » (Xenakis, 1992: 373). For Gabor, all sound can be considered an integration of quanta of acoustic energy, each quantum having its frequency, amplitude, duration and position in time. Frequency, amplitude and time must be resolved into discrete values (Δt Δf, Δg).

In Gabor's representation, a formal definition is necessary of the basic functions, and another formal definition is necessary for their integration. As basic functions, Gabor considered elementary signals of the kind

$g(t) = \exp [(- \pi / \sigma) (t - t_0)2] \exp [(i2\pi f_0 t)]$

that is, sine and cosine functions with a short Gaussian amplitude envelope. The value of parameter σ determines the duration (and hence the frequency bandwidth) for the elementary signal, such that Δt (width of the time unit) and Δf (width of frequency unit) are inversely proportional to the square root of the parameter:

$\Delta t = \sqrt{\sigma}$

$\Delta f = 1 / \sqrt{\sigma}$

It is theoretically possible, then, to expand a signal into small unit cells (Gabor's term was "logons") having unit area:

$\Delta f / \Delta t = 1$

$\Delta t / \Delta f = \sigma.$

Gabor series expansion can be written as

$s(t) \approx \Sigma_{j,k} \mathrm{C}_{j,k}\, g(t\, ; j \sqrt{\sigma},\ k\, 2\, \pi / \sqrt{\sigma}\,)$

Notice that for $\sigma = \infty$, the elementary signal equals a harmonic oscillation (periodic function, sine or cosine), while for $\sigma = 0$, the elementary signal becomes a "delta function", a pulse signal, the shortest imaginable change, known as the Dirac function. That means – as first observed by Léon Brillouin in 1959 (*Science and Information Theory*) – that the Gabor series expansion includes limit-cases representing the Fourier series, on the one hand, and a sequence of discrete digital samples (as described by the Shannon-Nyquist sampling theorem), on the other. In other words, the Gabor quantum-oriented representation provides a theoretical frame where continous and discrete representations of signals are special cases.[15] That has a direct analogy with quantum mechanics: according to Heisenberg's uncertainty principle, the more precisely the position of some particle is determined, the less precisely its momentum can be known, and *viceversa*. In our context it means that a precise measure in the frequency domain is at the cost of a

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[15] See discussion in (Orcalli, 1993: 313-317).

coarser indetermination in the time domain, and *viceversa*. In Gabor representation, precision in frequency ($\sigma \rightarrow \infty$) is at the expenses of precision in time (elementary signals become infinite harmonic oscillations), and precision in time ($\sigma \rightarrow 0$) is at expenses of precision in frequency (elementary signals precisely located in time are infinitely short pulses, ideally Dirac functions, whose spectrum is theoretically infinite).

It is relevant to observe that, for Gabor, a quantum approach was consistent with sound as a perceptual phenomenon, as something that is heard. He explained how his description may mirror the way the ear mechanism works, finding experimental evidence to that in work pursued by other researchers. Not by chance, then, it was by addressing issues of auditory perception and psychophysiology that Xenakis introduced his hypothesis of granular sound (Xenakis, 1960: 90-93; Xenakis, 1963: 65-68; Xenakis, 1992: 45-50).

4.3 XENAKIS' SOURCES FOR GRANULAR SOUND

Xenakis read of Gabor's approach on sound and hearing most probably in Wener Meyer-Eppler's 1959 book (*Grundlagen und Anwendungen der Informations Theorie*), which was in fact listed in his 1960 bibliographical references (Xenakis, 1960: 86; Xenakis, 1963: 61 and 225). It is possible that the composer attended Meyer-Eppler's lecture in Gravesano in 1955 (it seems that, in the occasion, the German researcher illustrated the Gabor's matrix, most probably for the first time before an audience including musicians).[16] Also in 1955, Meyer-Eppler published a paper (in the review *Die Rehie*, edited by Herbert Eimert and Karlheinz Stockhausen) touching upon issues such as « statistic problems of sound », « aleatoric modulation » (Meyer-Eppler, 1958: the original German publication dates from 1955) which lead us « directly into a world of phenomena previously described as *noises* » (Meyer-Eppler, 1958: 56). He noted that « formal criteria of various order » should be considered in studying sound: « the first order contains all observations concerning the statistical distribution of sound elements themselves […] The second order ("Markoff chains") and all higher orders take into account the […] transfer from one element to another or between further distant elements and their contextual relationships […] » (Meyer-Eppler, 1958: 57). In sum, the German author raised in that paper questions that must have been direct relevance to Xenakis.

In the Preface to the 1992 edition of *Formalized Music*, Xenakis wanted to make a difference between his research in granular sound (« which I started from 1958 ») and the formal frame proposed by Gabor, to whom Xenakis' research, now, had been « wrongly attributed » (Xenakis, 1992: xiii). He preferred to link his hypothesis of the granular nature of sound to earlier proposals by Albert Einstein, presumably dating from 1917-18. In analogy with Einstein's "photons" (quanta of light), Xenakis used the term "phonons"

[16] This conjecture is found in (Solomos, 2006: 7); see also (Roads, 2001: 62). As is known, most of the writings that Xenakis collected in his first book *Musiques Formelles* (1963) had been already published in the review *Gravesaner Blätter*, upon the initiative of Hermann Scherchen, orchestra conductor, at the time one of Xenakis' mentors. In those years, Scherchen organized an annual conference, with international contributors discussing contemporary and electronic music, as well as technical reports in audio and sound engineering. Xenakis wrote *Syrmos* to give Scherchen, to whom he dedicated the piece, a more convincing application of markovian stochastic music, the conductor not being conviced by *Analogique A et B*.

(quanta of sound) (Xenakis, 1992: xiii; Restagno, 1988: 30; Varga, 1996: 197). However, the composer did not qualify this point any further, nor did he provide detailed references to Einstein's publications. Overall, it is not at all clear why he felt that his idea of granular sound was to be re-positioned in the shadow of Einstein and kept away from Gabor, whom Xenakis himself had mentioned since his first paper on markovian stochastic music (written 1959, published 1960). One can reasonably think of a question of prestige. However, Gabor was an internationally renowned authority, and in 1971 received the Nobel prize for physics. If we trust his later memories, Xenakis in 1958 did not know Gabor's work (Restagno, 1988: 30) and « realized only later that [his hypothesis of the granular representation of sound] had already been proposed in physics » (Varga, 1996: 197). From that, we must conclude that he came to know of Gabor when work for *Analogique B* had already started (winter 1958-59), anyway well into the year 1959, probably after reading Meyer-Eppler's book. Xenakis had referred to Gabor in the 1959-60 paper presumably in order to let his hypothesis of the granular nature of sound lean on scientifically acceptable grounds, as a cautios way to put forth his own idea.[17] Also, Xenakis probably wanted to distinguish his approach of granular *synthesis*, that he developed « purely by intuition » (Varga, 1996: 197), from Gabor's formal *analytical* frame, which at that time had received no interpretation as a basis for sound synthesis.[18]

4.4 THE QUESTION OF 2ND-ORDER SONORITIES

Together with the hypothesis of the granular nature of sound, Xenakis put forth another important idea (similar to, but not identical with, Meyer-Eppler's own, mentioned above). He proposed that each cell in the Gabor matrix could represent not just a single sound particle (« not only a pure frequency and its satellite intensity » [Xenakis, 1960: 90; Xenakis, 1992: 47]) but an entire constellation of previously arranged grains (« a structure of elementary particles arranged a priori » [Xenakis, 1960: 90]). He added, « we think that a sonority of second order and even third order etc. could be created in this way » (Xenakis, 1960: 90). In my view, that represents a generalization of the initial hypothesis: larger-scale sonic structures – we may call them "sonorities", "gestures", … "music" – could emerge from a process starting in the composition of sound itself, that is, at sound synthesis level (Di Scipio, 1994; Di Scipio, 1997).

The emergence of higher order sonorities must be considered a prerequisite for all quantum-based synthesis methods: in principle, a single grain of sound *per se* is of no perceptual relevance, only amounts of patterned grains give rise to perceptually relevant phenomena. In Xenakis' own terms, « the elementary particles are of no importance on the level we have chosen. Only the groups of particles and the group characteristics can reasonably be considered » (Xenakis, 1960: 93). This is quite interesting, and opens to issues discussed in much later research of auditory scene analysis (Albert Bregman). Here we can't discuss

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[17] This caution is also evident from the "hypothetical" value of Xenakis' formulation, also qualified as a « temporary hypothesis » (Xenakis, 1992: 43). On this point, see also footnote 13.

[18] Gabor's own practical experimentation, in the 1940s, included experiments in the analysis and *transformation* of sound – not in sound *synthesis*. He exploited electro-optical technology (sound recorded on films) to process the sound signal in ways similar to what we today call "pitch-shifting" and "time-stretching" (Roads, 2001: 61). In the 1950s, a device was commercially produced by German

this point in depth. I must only emphasize the concept that, as it seems, markovian stochastics had really for Xenakis to fulfill a task of "synthesis", i.e. to shape a constallation of sound atoms whose audible result is a sonic entity of some kind: sound here becomes something to let happen from a lower-level process. More precisely it emerges from a stochastic process where sound particles overlap and interact in such a way that they eventually fuse together and transcend into a whole, into an individual sonority.

Now, it is not at all obvious whether stochastics could really provide a viable way to the particular task. In any case, surely Xenakis lacked the technology to accomplish the necessary density of sound events. That probably explains the relative failure in the emergence of 2^{nd}-order sonorities in *Analogique B*: only in some passages grains fuse together and are not heard as individual smaller units.[19]

5. FROM GRANULAR SYNTHESIS TO STOCHASTIC SYNTHESIS

Xenakis never returned to granular synthesis after *Analogique B*. He was not satisfied with the results he had achieved and, in any case, the task had required technical processes too cumbersome and unpractical to be ever repeated. He probably hoped that one day he could use computers to move further along this line.[20] Yet, even when he finally had access to computers and digital audio facilities, the composer did not venture to take the effort up again.

However, it would be wrong to say that, with *Analogique B*, Xenakis had finished with granular or quantum-oriented representations of sound. When he started research in "direct stochastic synthesis" with computers (early 1970s), in a way he was just moving from the level of grains (elementary signals with durations of approximately 0.04") to the even smaller level of samples (digital samples, elementary signals with durations of approximately 0.00002"). With that move, microcomposition shifted to a more finely grained scale in the sound signal. In a way, the approach was still reflecting the Gabor quantum-oriented representation of sound, only, it had left the general formalism for the special case where $\sigma \rightarrow 0$ (approximation of Dirac functions, as allowed by the available technology). Gabor bidimensional matrix had been implicitly squeezed into a monodimensional vector, a string, and that is the exactly the same as working with *pulse code modulation*, the most general digital coding of sound waves.

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manufacturers, the Zeitregler (also known as tempophone), based on similar techniques, that was utilized a.o. by Berio in *Thema (Omaggio a Joyce)*, 1958, and by Eimert in *Epitaph fur Aikichi Kuboyama*, 1964.

[19] See discussion in (Di Scipio, 1997). In (Di Scipio, 2006) some suggestions are elaborated about the technical process in the realization of the *Analogique B* tape.

[20] According to one author (LePrince-Ringuet, 1981), at the time of *Analogique A et B* Xenakis did try to access computers, but unsuccesfully. In 1963 he provided some details for a possible computer implementation of granular synthesis as in *Analogique B*: « the grains [would be] realized from waveforms duly programmed according to Gabor's signals », while « a second program would provide the construction [i.e. arrangement of grains] » (Xenakis, 1963: 72; Xenakis, 1992: 54). Notice the twofold methodology: one program does the synthesis, and another schedules the data assigned to the synthesis variables. That reflects a typical dualism of "instrument" (synthesis algorithm) and "score" (data passed on to the synthesis algorithm) found in most computer music languages (such as the Music5 and the likes). However, in Xenakis' case data for the synthesis level are provided procedurally (algorithmically) not in a declarative fashion (Di Scipio, 1994). A similar design is in the computer programs Xenakis wrote to compose *Gendy3* (1991).

This new sound synthesis approach was « the most economical way to create a plane wave in an amplitude-time space » (Xenakis, 1992: 289), as it consisted in the direct specification of strings of digital samples, that is, in the sequencing of millions of discrete amplitude values. There again stochastics was for Xenakis *the* key to sound synthesis, as he was calculating the discrete amplitude values (the digital samples) with stochastic functions. This research sometimes goes under the heading of *stochastic synthesis*.[21]

In addition, Xenakis (1992: 249) suggests that sounds thus generated « could be injected into the ST computer program » (that he had created some 10 years before as a tool of algorithmically implented stochastic music composition), and even that they could be organized using « Markovian stochastic processes » (implemented 15 years before, in *Analogique A et B*). There again we see the idea that an audible Gestalt is created by microlevel processes and is developed at a macrolevel following again stochastic methods. That task was to be actually accomplished much later, in a different technological frame, with Xenakis' ultimate and most thoroughly-going adventure in computer music, namely *dynamic stochastic synthesis* and related software – out of which *Gendy3* (1991) and *S.709* (1994) were born.[22]

6. CONCLUSIONS

From such observations, we must conclude that there is a striking continuity between Xenakis' his pioneering efforts in granular synthesis (1958-59) and later achievements in sound synthesis (1970s and 1990s). We may also ask: *where* in fact is "stochastic music" after 1959?

In the early 1960s, Xenakis ventured into computer programming and wrote the ST(ochastic) program. With that he worked out a series of five algorithmically composed pieces, for various instrumental ensembles. However, in many aspects the ST project was nothing new but for the computerized implementation: it was rooted in the theory of free stochastic music that was behind the 1956 composition *Achorripsis* (notice that the five ST pieces share one and the same date of composition: 1956-62). Later explorations – with "random walks", "Brownian motions", "arborescences" – are also at home in a probabilistic frame, and represent little more than particular extensions to the theory of stochastic music ("random walks" and "Brownian motions" are formally described as stochastic processes). After 1960 the composer turned to a variety of new projects, including instrumental incarnations of game theory (Xenakis, 1992: Chapter IV) and symbolic music (Xenakis, 1992: Chapter VI). He also approached Greek theatre and literature – starting with *Polla ta Dhina* (for children choir and orchestra, 1962) and *Oresteïa* (for mixed choir and ensemble, 1965-66), and worked very hard on challenging multimedia projects, starting with the *Polytope de Montréal* (1967). Later came new efforts in formalized music not directly

[21] In *New Proposals in Microsound Structure* – a paper from the early 1970s (Xenakis, 1992: 242-254) – Xenakis listed several probability functions that he could use for direct sound synthesis with computers. Sound materials thus achieved are comprised in *La Legend d'Eer* (multitrack tape music for the *Diatope*, 1977) and (according to some authors) in the music for *Polytope de Cluny* (1972). However, no one knows what particular functions did he actually use for such applications among the several that are listed in the paper. The graphical examples in that paper show short wave segments of a sort Xenakis could have generated with his methods, but no evidence is there that they were actually included in compositional work.

[22] Dynamic stochastic synthesis is described in (Xenakis, 1992: Chapter XIII and Chapter XIV).

connected to a probabilistic framework (sieve theory and cellular automata), and the UPIC graphical computer music system.[23] In general, after *Analogique A et B* and *Syrmos*, the utilization of stochastics was drastically reduced.

However, the stochastic approach continued in projects where computer-generated sounds were involved (*Polytope de Cluny*, *La Legend d'Eer*) and where fully automated computer-generated music was the ultimate goal (*Gendy3* and *S.709*). In such projects, Xenakis' methods of microcomposition were still leaning on a quantum-oriented framework for the representation of sound, as we have seen in the previous section, and that was certainly crucial to create the kind of particle-like, tactile and powerful sonorities that these works share with other Xenakian electroacoustic compositions.

If that is correct, then we should say that stochastics and granular sound remained closely interconnected in Xenakis' mind through the years. Although Xenakis explored them separately in several occasions, they do appear as intimately intertwining dimensions of the same compositional inspiration.

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[23] See (Solomos, 2004) for a comprehensive overview of Xenakian "theories".

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