Meta-Xenakis: Developing Style-Agnostic, Stochastic Algorithmic Music

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ABSTRACT

Iannis Xenakis was a pioneer in algorithmic composition of music and art. He combined architecture, mathematics, music, and performance art to create avant-garde compositions and performances that are still being analyzed, performed widely, and discussed today. Xenakis's musical contributions are deeply algorithmic in nature, inspired by his appreciation and understanding of mathematics and controlled randomness, i.e., stochastic processes.

This paper argues that Xenakis's algorithmic approach is style-agnostic, as it may be used with different sonification choices to produce pieces with more traditional aesthetics, possibly bringing broader acceptance, appreciation, and application of his techniques and ideas to more traditional compositional spaces. Also, today's music technology has evolved tremendously, through the integration of artificial intelligence, advanced computing algorithms, and human-computer interaction – techniques and technology that were unavailable to Xenakis, but which would have been inline with his pioneering spirit.

We explore some of Xenakis's early works in algorithmic and stochastic music, and reimagine the types of music Xenakis could possibly be making today, having access to the modern technology of smartphones and computing devices. Examples include a retelling of Xenakis's "Concret PH" using smartphones for sound spatialization and audience interaction / participation; "Éolienne PH", an example piece which utilizes the same statistical distributions as "Concret PH" to produce a completely different sound aesthetic; "on the Fractal Nature of Being…" which combines Xenakis's stochastic / aleatoric techniques with traditional music theory and modern mathematics / fractal geometry; and, finally "Nereides / Νηρηΐδες", a piano miniature piece, which is made using statistical distributions from a cloudy sky. We close with some general ideas on the future of the Algorithmic Arts.

1. INTRODUCTION

Iannis Xenakis was a pioneer in algorithmic composition of music and art. He combined architecture, mathematics, music, and performance art to create avant-garde compositions and performances that are still being analyzed, performed widely, and discussed today [1-9]. The compositions and other artifacts created by him were primarily inspired by his deep appreciation and understanding of algorithms, mathematics, and the use of controlled randomness, i.e., stochastic processes.

Given the evolution of the field of Computer Science since that time, Xenakis's work now falls clearly within in the field of the Algorithmic Arts (AlgoArts).[1] Xenakis's many musical contributions are deeply algorithmic in nature. Therefore, his rich and influential output would not have been possible without the ability to implement his processes through computer programming languages, such as FORTRAN and BASIC [10, 11], and the formalization, standardization, and replicability that such programming languages provide.

This paper is based on an invited talk-performance at the Music Library of Greece, in the context of "Meta–Xenakis" – a year-long, transcontinental celebration of the life and work of Iannis Xenakis (1922-2001). The word "meta" comes from the Greek "μετά", which means:

- "transcending", in a theoretical (or structural) sense, i.e., "higher level"; and
- "after", in a temporal (or spatial) sense, i.e., "afterwards" or "beyond".

In what follows, we engage with both notions of "meta". First, we explore the algorithmic side of Xenakis, through some of his works in algorithmic and stochastic music. Then, we reimagine the types of music Xenakis could possibly be making today, having access to the modern technology of smartphones and computing devices. The paper includes musical examples that hopefully demonstrate the points made.

2. THE ALGORITHMIC XENAKIS

In music and art, algorithms appear as early as Guido d'Arezzo (ca. 1000 A.D.), and in compositions of J.S. Bach, Mozart, John Cage, and Iannis Xenakis, as well as in the visual works of M.C. Escher, Roman Verostko, Vera Molnár, and Ernest Edmonds, among others.

Many sources on Xenakis are written by and for musicologists, music composers, and performers, and as such focus on the musical output that Xenakis created, e.g. [8, 12]. This is reasonable, as Xenakis was primarily known as a music composer. Fewer works have been written on the meta-level, algorithmic side of Xenakis – i.e., the algorithms or processes he created to generate

[1] This work is co-sponsored by the US National Science Foundation and the National Endowment for the Arts (#2139786), "Computing in the Arts – The Algorithm is the Medium", see http://AlgoArts.org .

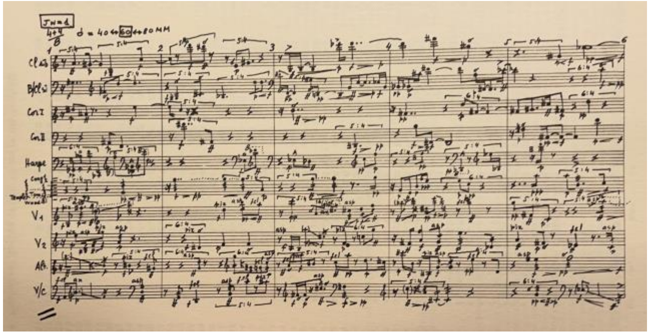

Figure 1. Example of the musical output of Xenakis's ST compositional process – first five measures of *ST/10-1, 080262* [11, p. 154].

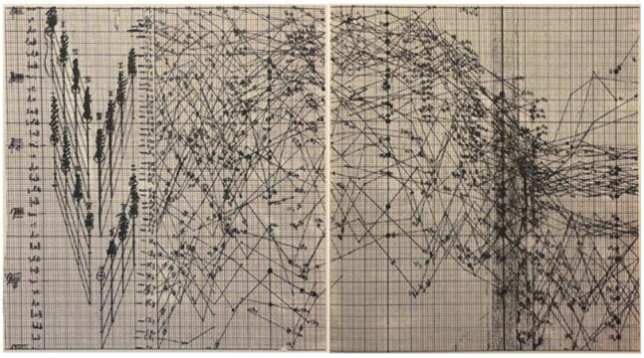

Figure 2. Example of sonification design to map the numerical output from the ST program to musical notation [11, p. 18–19]. The vertical axis represents solfege pitches, and the horizontal axis represents time.

musical artifacts. Notable examples of such meta-level analyses are included in [6, 11, 13].

This section focuses on Xenakis's algorithmic process. It discusses an example of mathematical modeling, sonification, and computer programming he used in musical compositions.

By focusing on the algorithms used to generate pieces, Xenakis clearly placed great importance on them, decades before algorithmic music composition became an established field.

For instance, Xenakis included the complete ST (Stochastic Music) program in his seminal book, written in FORTRAN – the state-of-the-art, high-level programming language, at the time. By doing so, he indicated the autonomy, and significance of algorithms in his compositional approach [11, p. 145-152]. The following section begins to explore this autonomy further.

2.1 Input → Process → Output

All artifacts surrounding us (chairs, computers, smartphones) may be analyzed in terms of:

- the *process* that created them;
- the *input* to this process; and
- the *output* of this process.

In the case of music and art, *the process is usually hidden* (or protected) behind a veil of mystery (or secrecy), as few artists share their process openly with the world. On the other hand, *the input to the process*, the source materials (or inspiration) are available to us, usually from conversations with the artists. For instance, Debussy created harmonic material from gazing at colorful landscapes. Finally, *the output of the process* – the actual artifacts – are always available to experience, inspect, interpret, and evaluate. It is by experiencing these artifacts that people are attracted to, or not – as the case may be with Xenakis, or say, Jackson Pollock – to a particular composer, or artist.[2]

In terms of *process* and *input*, Xenakis used algorithms and mathematical models to compose much of his music. For instance, he presents a thorough, eight-step process in [11, p. 22]. His process is clearly influenced by early software development processes, e.g., [14, p. 248-249]. However, it is his musical *output* that most people experience first. For example, Figure 1 shows the first few bars from *ST/10-1, 080262* (i.e., composed February 8, 1962). To compose this piece, Xenakis used his ST program (discussed above).

To fully appreciate this example, let us explore the input, process, and output:

- The *input* to the process consists of numerical data.
- The *process* is described by the program itself.
- The *output* generated by the program is just a sequence of numbers.

Given this *numerical output*, there are several possibilities, of course, for what to do with it:

- One possibility is *data visualization*, i.e., take the numerical output and convert it to visual drawings, or charts. Such visualizations may be information preserving, or focusing more on aesthetic or artistic outcome (i.e., without necessarily preserving accuracy). For example, consider visual charts for weather or stock-market reporting / forecasting.
- Another possibility is *data sonification,* i.e., take the numerical output and convert it to sounds or a musical composition. This is mainly what Xenakis did in his ST works.
- Yet another possibility is *data materialization*. The term is relatively recent [16], and refers to something Xenakis did do, i.e., take the numerical output and convert it to physical form.[3]

Figure 2 shows one of Xenakis's *sonification* designs, where he translates numerical data to sound. He uses solfege pitches on the Y (vertical) axis, and time on the X (horizontal) axis. The dots are actual numerical outputs, which are mapped to notes. Finally, he draws lines to connect the notes.

Xenakis uses an elaborate sonification design, to generate the *musical output*, by mapping the numerical output to musical notation. He chooses to sonify these numerical data as large masses of musical point-notes.

[2] Jackson Pollock's process generated artifacts with similar statistical properties to Xenakis's [15].

[3] This is the case, for example, with the architectural design of the Philips Pavilion [17, 18].

There are other possibilities, as will be shown later in the paper. These point-notes are mapped to string *pizzicati*, *glissandi*, and other aleatoric and stochastic microsound events, to be interpreted by – again – chosen orchestral instruments and performers (also, see section 3).

This mapping is stochastic, in that some aspects of the performance are approximate (and may even be unplayable); these aspects are left to be interpretated (or approximated by) the performers.[4]

The final piece is eventually performed by musicians, who interpret (or approximate) the musical score, adding subtle layers of breathing, hesitation, movement, simplification, and micro-textures to the sonic outcome.

The challenging nature of Xenakis's musical scores, generated through this compositional process, is captured in the following:[5]

> Of the many pianists who have performed and discussed *Evryali*, dedicatee Marie-Françoise Bucquet perhaps best expresses the performance issues Xenakis raised, writing, "Supreme challenge: he asks us to take risks and overwhelming responsibilities. I find it wonderful that instead of saying to the performer 'I have written this piece for you, and you are going to play it,' he said to me 'Here is the piece. Look at it, and if you think you can do something with it, play it'." [18, p. 74].

2.2 Style Agnosticism

Here, finally, it is important to emphasize that Xenakis chose the way his works sound – he meticulously crafted his *sound aesthetic*, through his sonification choices. In other words, his particular sound aesthetic is mainly the result of the *second part* of his compositional process – his sonification design.

The first part, i.e., his algorithmic approach is *style-agnostic*, and as such it can be used with other sonification choices, bringing possibly broader acceptance, and application of his techniques to other compositional spaces.

This is a significant point, which will be demonstrated further below with specific musical examples.

2.3 Authorship Attribution

Authorship attribution (or, "who is the composer?") is a significant question, often arising in the context of algorithmic music composition. Sometimes this may confuse even experts in computer science.

For example, given the above example (ST/10-1, 080262), let's explore who the composer is… Possible answers include:

- Carl Friedrich Gauss, the German mathematician who created the *probabilities* used for input in Xenakis's work.
- The computer – an IBM 7090 – which executed the ST program and produced the *output numbers*.
- Xenakis who created (a) the *process*, or *algorithm*, AND (b) the *sonification design* used to generate the final music score.

Interestingly, in the original talk (upon which this paper is based), from an audience of about 160 people, 3 identified Gauss as the composer, 3 identified the computer as the composer(!!), while the rest identified Xenakis as the composer. While this is not statistically significant by any means, it demonstrates the confusion general audiences may have with the question of authorship, when computers and algorithms are involved.

For the ICMC reader, of course, the answer is clear: The algorithm created the musical output. The computer (*blindly*) followed the algorithm. Xenakis wrote the algorithm – therefore, *Xenakis is the composer*.

However, the question of authorship becomes more nuanced when the input to the process becomes statistical probabilities derived from other composers' musical works, such as J.S. Bach, Mozart, or Beethoven – e.g., see [19-23].

Recently, this has become a controversial topic, given the availability of software systems trained with statistical probabilities from large language models (LLMs), such as ChatGPT and DALL·E [24, 25].

Regardless, this demonstrates the power of the algorithm as a creative medium, and strengthens our appreciation for Xenakis's vision and pioneering work.

3. STOCHASTIC MUSIC

Xenakis coined the term *stochastic music* (from the Greek stochos, "στόχος", or target), to describe music that evolves over time, within certain statistical tendencies and densities, and has points of origin and destination.

Xenakis created stochastic music to react to purely chaotic, random properties of 12-tone, or serialist music [11]. He believed the listener may be aesthetically overwhelmed by the complexity of serialist music – which, although deterministic due to its rules of creation, by definition, over time sounds utterly chaotic (i.e., uniformly distributed). He proposed to use statistical mathematics to produce compositional techniques, whose musical outcome is more controllable. This could produce music that is more aesthetically-pleasing – at least structurally, which he went on to demonstrate.

His first electroacoustic composition, *Concret PH* (1958), was composed intuitively (i.e., non-algorithmically, by ear) to demonstrate this.

Xenakis also created programs to assist in the compositional process. One major example is the *Unite Polygogique Informatique de CEMAMu (UPIC)* system. UPIC was constructed in 1977 by Xenakis and his associates to connect visual drawing (e.g., architectural drafting) with musical or sound design. This was done to achieve "sonic realization of drawn musical ideas by a computer" [26, p. 252].

We have reconstructed a simplified version of UPIC, in Python. To do so, we used *JythonMusic*, an environment

[4] For instance, in *Evryali* (1973), Xenakis overlooks the fact "that the two hands and ten fingers of the pianist can only reach so far … and even includes a high C#, beyond the range of any piano" [18, p. 75].

[5] One may argue that this contributes to why he is admired by some musicians, while avoided by others.

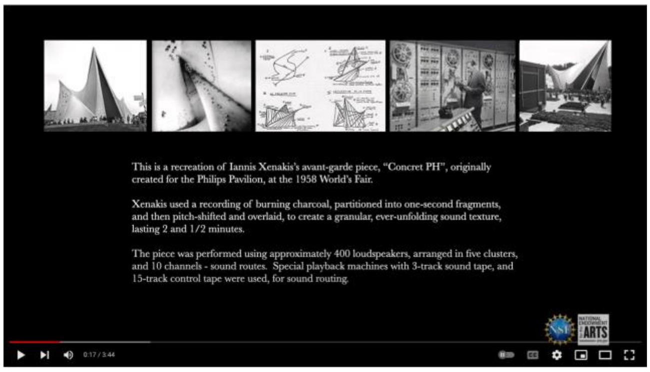

Figure 3. Performance of *Concret PH – A Retelling*, using smartphones, at the University of Maryland, College Park, USA, April 2022 – https://youtu.be/sCe2qQi_QBY

for developing interactive musical experiences, and systems for computer-aided analysis, composition, and performance in music and art.[6] JythonMusic has been used for research in music information retrieval and computational musicology, as well as in modeling aesthetics and creativity, sound spatialization, and telematics.

Our UPIC implementation expands on the original to control various aspects of a musical piece through curves. Although we have implemented a simple graphical user interface for drawing curves and generating sounds in real-time, in our work, we find it more useful to simply output numerical sequences – x and y coordinates of graph points, and then incorporate them algorithmically into other programs.

In our approach, UPIC graphs may describe densities of *pitch*, *dynamic*, *harmonic probability* or *consonance*, *timbre* or *various instruments*, occurrence of *arbitrary sonic events* – as these unfold over time (or relative to each other). In fact, these graphs can model any musical attribute desired, as long as it can be controlled via algorithmic means. Since this is done in Python, such graphs can also control aspects of other algorithmic processes, including parameters of external sound engines (e.g., Ableton Live), visualizations, animation parameters, and arguments to arbitrary Python functions, thus tapping into the full power of a Turing Machine.[7]

4. CASE STUDIES

This section presents music examples, derived from Xenakis's work, suggesting a few possibilities of how to move forward (i.e., the "afterwards" or "beyond" meaning of "meta"). These demonstrate that it is possible to create *style-agnostic*, stochastic algorithmic music, based on Xenakis's original ideas and contributions. Also, they incorporate modern technology, more advanced algorithms, and use of smartphones for sound spatialization and audience interaction / participation.

[6] See http://jythonMusic.org .

[7] A great alternative, also inspired by UPIC, is the graphical environment *IanniX*, a 3D sequencer for digital art and real-time control (see https://www.iannix.org).

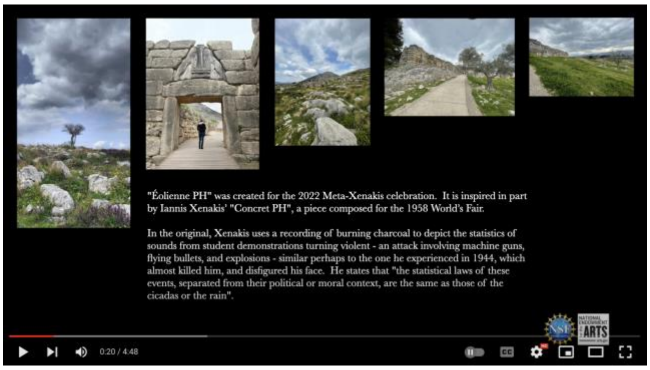

Figure 4. Performance of *Éolienne PH*, at the International Symposium on Electronic Art (ISEA 2022), Barcelona, Spain, June 2022. It includes photographs from the performance site of Mycenae Polytopon (1978) – https://youtu.be/mNBwNrpwdaA

4.1 *Concret PH – A Retelling* (2022)

Concret PH (1958) is an early and influential piece of stochastic music, composed by Xenakis intuitively, to capture mathematical probabilities he was deeply interested in. It was performed in the Philips Pavilion at the 1958 World's Fair, using approximately 400 loudspeakers – arranged in five clusters, and 10 channels, or sound routes. Special playback machines with a 3-track sound tape, and a 15-track control tape were used for sound routing. Unfortunately, the Pavilion was demolished soon thereafter, so we cannot experience the piece as it was originally intended / performed [5, 9, 17].

Our recreation of *Concret PH* utilizes speakers on audience smartphones, to recreate the multiplicity and apparent unpredictability of sound sources of the original, as well as audience movement through the performance space. We utilize our UPIC approach to control the density of sound events over time, in order to recreate the unfolding sound densities and textures of the original.

In the original, Xenakis used tape recordings of burning charcoal, partitioned into one-second fragments, pitch-shifted and overlaid, to create granular, unfolding sound textures. Our recreation uses sounds from the original, together with *hammer-on-anvil* sounds, to simulate individual charcoal sound events.

Our code distributes the required number of sound events across all participating audience smartphones. This works regardless of how many smartphones are participating. The piece may be reproduced using a single smartphone, as well as hundreds of them, always maintaining the desired density and sound texture. Participants are asked to move around freely, resembling people moving through the Philips Pavilion in 1958, to create a truly immersive experience [27].

Concret PH – A Retelling was first performed at the University of Maryland, College Park, USA in April 2022. A video link is available in Figure 3.[8]

[8] This performance was captured via a high-quality 3D binaural microphone, so stereo headphones are recommended.

4.2 *Éolienne PH (2022)*

Éolienne PH (or *Be the Wind*) was composed in the context of the 2022 Meta-Xenakis transcontinental celebration. It was performed at the *International Symposium on Electronic Art (ISEA 2022)* in Barcelona, in June 2022. It was partially inspired by the ISEA 2022 conference themes of "exploring our relationship with nature" and "transforming / inhabiting our world".

Éolienne PH is based on Xenakis's *Concret PH* (see previous subsection). It demonstrates the importance of separating the two parts in Xenakis's compositional process:

(a) the *algorithmic process* used to generate numerical data, and
(b) the *sonification choices* mapping these data to sounds.

It should be emphasized that *Éolienne PH* utilizes the *same probability density function* as its sister piece, *Concret PH – A Retelling*. In fact, they share the exact same code.

However, the sonification design of *Éolienne PH* employs natural, soothing sounds, such as flowing water, and birdsong. The piece was composed during COVID-19, and given the ISEA 2022 conference theme, the sonification choices were meant to create a restorative, meditative, and potentially healing experience. Similarly to its sister piece, these sounds are partitioned into small fragments, and then pitch-shifted and overlaid, to create a granular, ever-unfolding sound texture.

Éolienne PH utilizes audience smartphones to deliver its sounds. Participants are asked to move around, creating independent, aleatoric sound trajectories. This is also inspired by Xenakis's *Mycenae Polytopon* (1978) [28]. This free movement creates infinite possibilities for sound texture and placement, as each person traverses a unique and unpredictable sound path.

Finally, the composition allows participants to generate high-quality, binaural sounds of wind-chimes – tuned in C *Aeolian* scale – by tapping on their screens. This makes them active contributors to the unfolding soundscape, and invites (but does not require) deep listening, and potentially collaboration.

While identical to *Concret PH* in terms of algorithmic design, the new sonification scheme produces a completely different (diametrically opposing?) aesthetic experience, and emotional outcome. This demonstrates the intrinsic value, and independence from sonic outcome, of Xenakis's algorithmic and stochastic contributions.[9]

A video link is available in Figure 4.

4.3 ***on the Fractal Nature of Being…*** (2022)

The piece *on the Fractal Nature of Being…* was also composed in the context of the 2022 Meta-Xenakis transcontinental celebration. It was performed at the Music Library of Greece, in May 2022. This piece brings together everything discussed so far, exploring how stochastic and aleatoric techniques introduced by Xenakis may be combined with traditional music theory and modern mathematics / fractal geometry. Similarly to the previous two pieces, audience members are invited to participate via their smartphones, contributing to the performance via their speakers and accelerometers.

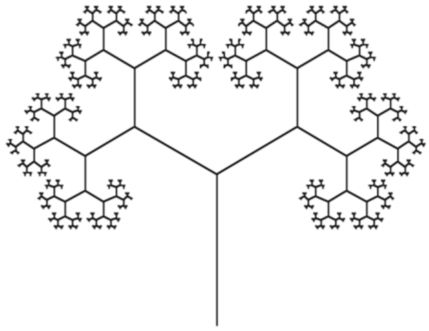

Figure 5. A golden tree is a fractal plant-like shape, incorporating the golden ratio, or φ (0.61803398…). The musical structure of *on the Fractal Nature of Being…* is based on this shape.

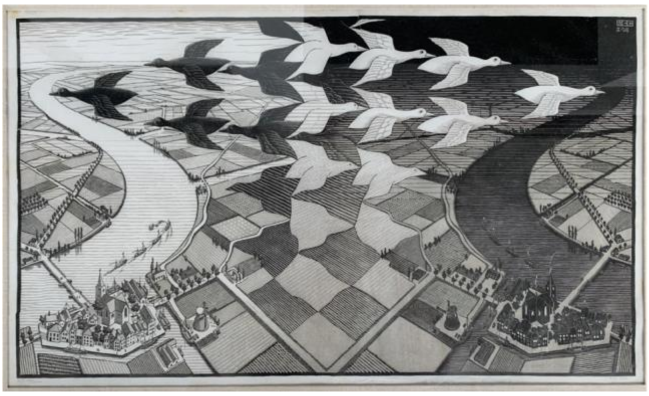

Figure 6. M.C. Escher's *Day and Night* (1938). The continuous transition between light and darkness, visually, best describes the sound transitions between consonance and dissonance in *on the Fractal Nature of Being…* (2022).

The piece is modeled after a fractal plant-like structure, or arborescence, known as the *golden tree*, which incorporates the golden ratio, or φ (0.61803398…), as shown in Figure 5. Following this structure, the piece is built from a one-minute-long harmonic theme, which serves as the "trunk" of the tree. This theme is expanded and embellished upon, at different levels of granularity, as the piece unfolds.

The fractal structure of the piece begins with the harmonic theme being introduced on the piano. As the piece unfolds, the theme is repeated at different levels of granularity, by different instruments – smartphones, cello, bassoon, and guitar – using tempo (faster), register (higher octaves), and randomness (improvised, aleatoric notes). This creates musical space for other instruments to enter, and the fractal to expand (i.e., become more detailed).

A UPIC-based probability density function controls the interplay between *consonance* and *dissonance*. This is a meta-Xenakian idea, as Xenakis mainly focused on the statistical interplay between sounds and silence.

[9] Also, this suggests that those who potentially dislike Xenakis's music, may only dislike his sonification choices.

Figure 7. Performance of *on the Fractal Nature of Being…* at the Music Library of Greece, Athens, Greece, May 2022. The piece utilizes audience smartphones for distributing sounds and controlling aspects of the performance – https://youtu.be/MG3l5v8FFbc

This idea is probably better communicated through M.C. Escher's *Day and Night* (1938), shown in Figure 6. Notice the continuous transition between light and darkness. This is similar to the continuous transition between consonance and dissonance in *on the Fractal Nature of Being…*

The piece moves through seven phases – each introducing a new instrument, while earlier instruments cyclically move to higher levels of detail (higher registers and faster tempi). The fifth phase introduces dissonance utilizing *stochastic probabilities* from the first 1½ minutes of Xenakis's *Metastaseis* (1953-4).[10] This phase also uses increased loudness of notes on smartphones, to highlight them – something that Xenakis was fond of (partially, due to his loss of hearing, caused by the tank shell explosion that almost took his life). Then, at the piece's golden ratio, the dissonance ends abruptly, and a new phase begins – with the bassoon entering to restore consonance. In the seventh and last phase, instruments go out one-by-one, ending the piece on an ambiguous interval (a major 2nd).

Smartphone sounds are aleatorically controlled via algorithm, while physical instruments improvise on the theme (in F minor scale), at different levels of granularity, based on their fractal level in the piece.

On the visual side, the performance includes fractal images displayed on a screen (see Figure 7), introducing a new image per phase, whose fractal properties (or entropy) are controlled by the accelerometers of participating audience smartphones. When the audience smartphones are still, the image's fractal structure is precisely the golden tree.[11]

A video link is available in Figure 7.[12]

4.4 *Nereides / Νηρηΐδες* (2022)

Xenakis was deeply interested in statistical properties of natural phenomena:

> [O]ther paths also led to the same stochastic crossroads—first of all, natural events such as the collision of hail or rain with hard surfaces, or the song of cicadas in a summer field. These sonic events are made out of thousands of isolated sounds; this multitude of sounds, seen here as a totality, is a new sonic event. This mass event is articulated and forms a plastic mold of time, which itself follows aleatory and stochastic laws. [11, pp. 8-9]

Interestingly, originating in a different (emotional, intuitive, non-mathematical) space, Claude Debussy makes a similar observation, in 1911:

> Who will discover the secret of musical composition? The sound of the sea, the curve of the horizon, the wind in the leaves, the cry of a bird, register complex impressions within us. Then suddenly, without any deliberate consent on our part, one of these memories issues forth to express itself in the language of music. It bears its own harmony within it. By no effort of ours can we achieve anything more truthful or accurate. ... No doubt, this simple musical grammar will jar some people. ... I foresee that and I rejoice in it. I shall do nothing to create adversaries, but neither shall I do anything to turn enmities into friendships (Debussy cited in [29, p. 226]).

It is intriguing to see how similar Xenakis and Debussy are – both being inspired by statistical properties of natural phenomena, and both being unapologetic about it. Still, they use different compositional tools and techniques – Xenakis, algorithmic and mathematical means, while Debussy, traditional (classical / impressionist) compositional processes [30].

Xenakis uses mathematical formulas to model natural phenomena. These formulas – being mathematical – are abstractions or generalizations, approximating trends in the actual data. They do not account for slight "imperfections" or noise, found in the original natural phenomena. Nature is never perfect, nor exactly ideal.[13]

This leads to the following compositional idea or "syllogism": What if, in an attempt to be more accurate in terms of natural imperfections, we bypassed the intermediate models of mathematical formulas (such as Gaussian or Poisson distributions) used by Xenakis (and others) to describe statistical tendencies of natural phenomena? Instead, what if we captured data directly from the natural phenomenon, since modern technology and computing allow us to do this relatively easily now? This way, we can use the exact distributions or fluctuations of densities in natural phenomena, for instance, through processing of *high-quality* audio recordings, or *high-resolution* digital images, among others.

Nereides / Νηρηΐδες is a four-hand, piano miniature piece, which demonstrates this approach. It explores the ever-unfolding interplay between sky and sea, or the evaporation-condensation-precipitation cycle. It is named

[10] See https://youtu.be/SZazYFchLRI .

[11] This can be seen later in the video of the piece's performance.

[12] This was on the last day of COVID-19 restrictions, so masks had to be worn. The following day, masks were removed.

[13] For example, Earth is not spherical, and its orbit is not a perfect ellipsis – there are small perturbations not captured by traditional geometrical or mathematical models, which tend to be ideal and approximate.

Figure 8. Source of thematic material for *Nereides / Νηρηΐδες*. Six trajectories, or curves, were selected intuitively (i.e., by ear) to capture the variety of white light distributions and densities – https://bit.ly/nereides1

after the female spirits of sea waters of Ancient Greece, the Nereides, that personify the cycle of water.

We used our UPIC approach to capture trajectories or curves of white light (luminosity) in the cloudy sky image, shown in Figure 8. We extracted the distributions of light straight from the source material (a high-resolution image), making deliberate choices where trajectories begin and end, and how they spread onto the piece's timeline – some lengthier, others shorter, some slower, others faster, some inverted, and so on. This is similar to Xenakis's own choices when using UPIC, i.e., where to draw shapes, how long to draw them, etc. Through this process, we selected six trajectories, or curves.

Nereides / Νηρηΐδες is then literally, and figuratively, a stochastic study of light in a cloudy sky. Moreover, it has a fractal, or self-similar structure. This is a direct result of the source material (i.e., cloud formations) being fractal [31]. The piece may sound deceptively simple. However, under the apparent musical simplicity, hides an intricate interweaving of pitches and rhythmic material that fit harmoniously together. The six musical trajectories, similarly to Xenakis's UPIC approach, were selected intuitively (i.e., non-algorithmically, by ear) to consist of reflective patterns. These patterns originated in the natural processes that produced these clouds.

A reduced, two-hand version of *Nereides / Νηρηΐδες* will be performed at the Megaron / The Athens Concert Hall in November 2023, as part of the celebration for the 70th anniversary of The Friends of Music Society of Greece.

An audio link is available in Figure 8.

5. CONCLUSIONS

The infusion of algorithms in the arts has increased dramatically since the greater availability of computers starting in the 1960s. All areas of art and entertainment, such as graphics, design, animation, sculpture, dance, theater, music, and film, to name a few, have been impacted greatly. At the same time, the inverse infusion of artistic creativity, design, and innovation into computing, engineering, and other scientific fields produces a creative tension, which leads to new ideas, and continues to produce new discoveries:

> Art and science are in a tension that is most fruitful when these disciplines observe and penetrate each other and experience how much of the other they themselves still contain. [32, p. 1]

As Xenakis similarly said:

> From here nothing prevents us from foreseeing a new relationship between the arts and the sciences, especially between the arts and mathematics: where the arts would consciously "set" problems which mathematics would then be obliged to solve through the invention of new theories. [33, p. 3]

We have finally reached a point where the algorithm has clearly been established as a very powerful, creative, and expressive medium, for artists and musicians. As we move forward into the 21st century, researchers, composers, artists, and educators are engaging algorithmically, and are interweaving algorithmic thinking and development of technological solutions, into their art theory and creative practice.

This raises a forward-thinking, yet inescapable question: Since algorithms have become such a powerful compositional tool, and a creative medium, when is the right time to begin teaching principles of algorithmic music composition (and computer programming), as part of a general, well-rounded music education curriculum?

The future demands "out-of-the-box" thinkers – people who will engage algorithmically to create new artifacts and techniques that have not been seen before. This is precisely what Xenakis did in a pioneering way, given how early he engaged with algorithms and computer programming, for musical and artistic purposes. His theoretical and artistic contributions continue to inspire and move us forward.

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