Non-linear Dynamical Systems
for Sound Synthesis and Music Composition:

a portfolio of creative works exploring their use and a discussion of the software tools developed

by

Hector Bravo Benard

Submitted to
The University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

Department of Music

College of Arts & Law

The University of Birmingham

August 2024

ABSTRACT

This document examines a portfolio of fixed media electroacoustic works, comprising five short studies and seven pieces created between 2020 and 2024. It provides an overview of the musical works and the underlying compositional ideas, with a particular focus on the use of non-linear dynamical systems and chaotic generators for sound synthesis, as these techniques played an integral role in the creation of each of the compositions. Additionally, the document discusses the challenges, motivations, and creative possibilities associated with working with such systems. It also offers insights into some of the software tools developed specifically for this purpose and their application within the pieces.

To my sister Susana, who has always been my best friend and greatest supporter, and from whom I have learned more than from anyone else in my life.

We both know that none of this would have been possible without you.

In loving memory of my dear Fee, my faithful friend who departed while I was finishing this document.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor, Scott Wilson, for his unwavering support and guidance throughout this journey. My sincere thanks also go to Annie Mahtani, the Department of Music at the University of Birmingham, and the entire BEAST community for their invaluable contributions. Christopher Haworth and Simon Emmerson provided insightful feedback during my viva examination, and I am very grateful for their suggestions and supportive and thoughtful comments.

I am especially grateful to René Uijlenhoet and Agostino Di Scipio for their friendship and their generous support and guidance over the last many years, through this and other PhD programs I was part of.

Lastly, I would like to thank my partner, Lisa, for her endless support, love, and patience, as well as my parents, family, and the many teachers, friends, partners, and colleagues who have helped shape my path over the years. I hope I will be able to somehow give back some of the love, support, and inspiration I have received from you over the years.

TABLE OF CONTENTS

INTRODUCTION

My exploration of non-linear dynamical systems in music composition stems from a lifelong fascination with noise, chaos theory, and their parallels with and potential applications in artistic creation. The unpredictable behaviors and emergent complexity of these systems mirror the intricate processes of musical evolution, where simple rules can generate surprisingly rich sonic worlds. This document presents a portfolio of electroacoustic works developed between 2020 and 2024, alongside the software tools I designed to implement these ideas in practice.

The following chapters delve into the synthesis of audio and control signals through chaotic processes, exploring both the creative potential and technical challenges of these systems. While previous composers, such as Iannis Xenakis and Agostino Di Scipio, have pioneered the use of stochastic and chaotic processes in music, my work seeks to build on these foundations by developing custom tools tailored to my compositional goals. By crafting bespoke software modules within a virtual modular environment, I aimed to create an intuitive playground for sonic exploration, balancing mathematical rigor with artistic freedom.

In addition to discussing the historical context and theoretical basis of these techniques, I outline my personal creative journey and how it led me to embrace chaos as a core element of my practice. I describe the compositional ideas behind each piece in the portfolio, the role of spatialization in structuring dense sonic layers, and the iterative process of refining both the tools and the music itself. Finally, I reflect on the future directions this work might take, including potential live performance applications and further explorations of granular synthesis and coupled chaotic systems.

This introduction opens the door to an exploration of how non-linear dynamical systems can inspire and shape musical material. It is not merely a technical study but a reflection on the interplay between technology and artistic expression, and how embracing uncertainty and complexity can open the door to different forms of musical discovery. In particular, this document presents some of the artistic results of this research in the form of original compositions, where the concepts and techniques discussed are explored and tested in practice.

NON-LINEAR DYNAMICAL SYSTEMS AND CHAOS

"One must still have chaos in oneself to be able to give birth to a dancing star."
— Friedrich Nietzsche

Introduction of the Basic Concepts

Non-linear dynamical systems are systems in which the state over time is determined by equations with non-linear relationships between their variables, often involving recursive processes. Unlike linear systems, the relationship between inputs and outputs is not proportional, which means that small changes in one part of the system can lead to disproportionate and unpredictable effects, a phenomenon known as sensitivity to initial conditions. These systems can exhibit behaviors that linear systems cannot, such as multiple stable states, bifurcation patterns, and chaos. They are often found in natural phenomena such as weather patterns, population dynamics, and electrical circuits, where outcomes are not simply the sum of their parts and can vary in unexpected ways (Strogatz, 2015).

A variety of non-linear dynamical systems can be modeled using simple mathematics with recursive functions, where the output feeds back into the input to calculate the system's state at each step. These systems can be implemented in software with just a few lines of code. Their complex behavior offers exciting possibilities for generating control and audio signals in sound synthesis and music creation. They also open the door to discovering emergent properties, where rich timbres and intricate musical structures arise from very simple rules and processes.

Some Historical Precedents

The use of non-linear dynamical systems in music is by no means new, both in composition systems and as signal generators for sound synthesis and music production. Some examples of this are described by Curtis Road (Roads, 1996) and Charles Dodge (Dodge, 1997) in their classic computer music texts from the 1990s. Barry Truax discussed the use of chaotic non-linear systems in sound synthesis in an article in 1990, outlining how they work and why they are appealing to explore in music (Truax, 1990).

Rick Bidlack has extensively explored the use of chaotic systems in music composition. In his doctoral dissertation, *Music from Chaos: Nonlinear Dynamical Systems as Generators of Musical Materials* (1990), he investigates how non-linear dynamical systems can generate musical materials. However, his thesis focuses on the technical aspects, and his aesthetic aims appear to differ significantly from my own in that he uses chaotic systems to generate note-based music rather than synthesized sounds and noise. He further examined the application of chaotic systems in composition in two articles published in 1992 (Bidlack, 1992a, 1992b).

Agostino Di Scipio has also written extensively about non-linear dynamical systems, and among other things he explored the use of iterated non-linear functions for sound synthesis (Di Scipio, 1996, 1999a, 2000). In his later work he moved away from the direct use of these tools for synthesis to the exploration of complex systems in live music through feedback networks and room-dependent signal processing (Di Scipio, 1999b, 2003). David Dunn[1] has also written about the use of chaotic systems in music and produced some interesting musical works focusing on their use (Dunn, 1997). More recently, Dunn has performed with custom-built chaotic circuits, as he did in a concert I attended in Seattle in 2014. James Harley has

---

[1] See his album *Autonomous and Dynamical Systems (2007)* for some examples.

discussed the use of algorithms adapted from chaos theory and generative processes in algorithmic compositions (Harley, 1994).

Many other researchers have proposed different algorithms involving non-linear dynamical systems for sound synthesis and instrument modelling, such as Lindeman (1988), Damiani et al. (1999), and Manzolli et al. (1999); Rodet (1995) has also discussed non-linear dynamical systems for physical modelling. Berdahl and Viator have recently explored sound synthesis by connecting a chaotic map to a bank of resonators (Berdahl and Viator, 2021), attempting to find a musically interesting balance between simplicity and randomness.

Systems of coupled oscillators for sound synthesis, a subject related to non-linear dynamical systems, have been discussed by several authors in recent publications, such as Lem and Orlarey (2019) and DeFilippo (2023). A lot of work has been done in the 2000s in the area of non-standard synthesis, especially trying to build on Xenakis's non-linear dynamical synthesis and using it in compositions, by authors such as Hoffman (2003), Luque (2009), Collins (2011), and Dobrenau (2011).

Personal Motivation

Ever since I first encountered non-linear dynamical systems and chaos theory as a teenager, I have been captivated by these concepts. The notion that simple mathematical systems can lead to intricate and unpredictable behaviors, offering profound insights into the natural phenomena we observe, sparked a deep fascination within me. I was also intrigued by the visual representations of dynamical systems, where abstract mathematical models generated intricate patterns and structures, often mirroring forms found in nature.[2] I was always curious about the possibilities of applying these ideas to music, but whenever I came across examples of this, I found the results extremely disappointing from an aesthetic point of view.

When I began studying composition at university, I discovered the music of Iannis Xenakis, and was immediately drawn to it. From an intellectual perspective, I was attracted by his use of mathematics to model natural phenomena in music, but I also found the actual results quite fascinating sonically. I started exploring the use of algorithmic methods in composition, at the time for instrumental music, and later I was able to study Xenakis' music and ideas more extensively at the Xenakis Center (CCMIX) in Paris, a year after his death, and later at the Institute of Sonology in the Netherlands, where I also studied other methods of algorithmic composition and synthesis more thoroughly.

During my time in Paris I also started exploring computer music, and experimented with sound synthesis through the use of Xenakis's UPIC system. I became interested in fixed media composition, especially in immersive multi-channel environments, and was influenced by the ideas and music of Trevor Wishart after meeting him at CCMIX. But my creative focus at the time was centered around instrumental music, and later live music with instruments and electronics. I created pieces that incorporated algorithmic techniques, primarily for live processing of instruments, and explored concepts related to dynamical systems and feedback networks. These explorations were greatly influenced by the music and ideas of Agostino Di Scipio. During the following years I continued focusing on live music, never really venturing into fixed media composition, aside from experiments that never fully developed into pieces.

[2] For an accessible overview of non-linear dynamical systems and chaos theory, see (Gleick, 1987), (Steward, 1989), and (Mitchell, 2009).

But over the years, at the same time that my interest in sound synthesis was developing further, I was also growing increasingly frustrated with my relationship with performers, partly due to my lack of social skills, and becoming increasingly dissatisfied with the academic and contemporary music scene in general. I started writing mostly music that I could perform myself with live electronics. Later, and partly as a result of my personal circumstances, I gradually shifted my focus completely to fixed media electroacoustic works, as this medium offered the greatest flexibility and allowed me to explore my musical ideas with complete freedom, without having to worry about dealing with performers or performance opportunities. Throughout this time, I also kept developing tools for my own use, especially as I became a better programmer, but for the most part, I kept these tools to myself. I also continued learning about non-linear dynamical systems and complexity, and followed several online courses on these subjects at the Santa Fe Institute, the leading research center for complex systems science. I also started working with modular synthesizers in the Eurorack format, and was fascinated by them, and by the variety of modules that existed.

Voltage Modular

In 2019 Cherry Audio launched the Voltage Modular platform, a software environment that emulates voltage control modular synthesizers. I began developing modules for this platform for commercial release –under my own *Benard* brand– and implementing some of the algorithmic composition tools that I had been using over the years. This situation also provided the perfect opportunity to revisit my passion for non-linear dynamical systems, and to explore and implement some of the systems capable of producing chaotic behavior as modules for the platform. Since I was releasing my modules as paid software, I was constantly looking for new ideas, driven in part by a clear financial motivation. Implementing chaotic systems as modules provided a wealth of options for new and innovative modules, making this prospect particularly appealing.[3] But the motivation also came from the need to have simple and reliable tools that I could use to explore sound synthesis with these systems in my own work and to create music.

Other Tools for Music Using Chaos

There are many commercial options available nowadays for using chaotic systems in sound synthesis. There have been several implementations of chaotic modules in hardware over the years, especially in the Eurorack format of modular synthesizers, such as the circuits developed by Ian Fritz, and modules by Nonlinear Circuits and Snazzy FX. A simple search in the Modulargrid platform[4] returns dozens of modules that claim to deal with chaos in some way, or that are directly modeled after chaotic systems.

In software, there have also been many implementations of chaotic systems for music, such as the classic chaos library of Max objects by Richard Dudas, later updated by André Sier, implementations of many chaotic generators in *SuperCollider*, some chaotic functions and systems implemented in *Kyma* by Carla Scaletti, and modules by Michael Hetrik in *Reaktor* Blocks and *VCV Rack* (and later also in *Voltage Modular*), along with many other implementations that have appeared in *Voltage Modular* and *VCV Rack* after the initial release of my own modules, to name just a few. There are also several VST softsynths that use chaotic generators for their oscillators and LFOs. Of particular notice is *Kult*, by Dawsome, which

---

[3] As a curious side note, my PhD was almost entirely funded by the profits from the sale of my software modules, though the chaos ones are only a small part of them.

[4] A website for exploring modular synthesizers and planning systems that has an archive of existing hardware modules.

allows the user to select a number of chaotic functions for its two oscillators, while also displaying their plotted images, and *Generate* by Newfangled Audio (Eventide), along with its free version *Pendulate*, which focus on the use of chaotic generators for sound synthesis. Even some of the more general and popular software synthesizers available today offer some kind of chaos control signals, such as the chaotic LFOs in *Falcon* and *Serum*, and the Lorenz attractor in *Vital*.[5]

It is evident from this that the field of electronic music has a strong interest in exploring and utilizing chaotic systems. This comes in part from the fact that they offer novel options for audio and control signal generation, being able to produce behavior ranging from quasi-periodic to seemingly completely random, by only making small adjustments to their system parameters, providing an interesting continuum between order and randomness that can be useful and appealing for music. For audio generation, they offer ways to produce a variety of sounds through what is sometimes referred to as non-standard methods (Koenig, 1978), and are great for creating all kinds of noises and lively textures with rich spectra.

Are Non-linear Dynamical Systems in Music Still Relevant Today?

It's been at least four decades since composers started exploring the use of non-linear dynamical systems in music. One might wonder if this topic is still relevant today, and what has changed during this time.

We have already briefly mentioned some of the more recent developments in the use of chaotic systems and related areas in music. Towards the end of his life, Xenakis was particularly focused on stochastic dynamical synthesis, as he saw this as the ultimate

[5] See Appendix B for a list of the hardware and software mentioned and corresponding links.

realization of some of his theoretical ideas (Xenakis, 1992). The subject has been revived by many composers since then, and it seems to be a topic that still generates a lot of interest, along with other forms of non-standard synthesis, all of which bare some relation to non-linear dynamical systems.

After his initial exploration of chaotic systems in music, Di Scipio moved to other ideas that grew out of this, such as his audible ecosystems and other pieces for performers and live electronics, focusing on systems of live interaction rather than on synthesis. But the exploration of non-linear dynamical systems in music paved the way for this, and it influenced his overall philosophy about music and composition (Di Scipio, 2003).[6]

My own path has been the opposite in the sense of moving from music with performers and live electronics to acousmatic music and a focus on synthesis, partly as a result of my own personal circumstances, as discussed earlier, at least at the present stage of my creative practice.

I wasn't drawn to the use of dynamical systems simply for its novelty value, or because I thought it was revolutionary in any way to use these tools in music at this point in time. I also don't consider those to be valid reasons to guide artistic work. But I believe that there is still a lot to be discovered, both in terms of synthesis and of musical creation, through the use of these tools and systems. In that sense I see myself as building on the legacy of Xenakis, Di Scipio, Dunn and other composers who have explored these subjects. Perhaps the contributions can be miniscule, but incremental development in the use of these systems is nevertheless valuable. My interest was also related to the exploration of noise and complex timbres, a purpose which these tools can serve be very well.

[6] I have discussed these topics directly with Di Scipio through personal communication at various points over the last 20 years.

I don't believe there is such a thing as objective progress in music in the same sense as there is in science or technology. No matter how new or sophisticated the techniques a composer uses, they are only valuable in as much as they serve the purpose of creating works of art, with their own goals and aesthetic and historical frames of reference. But we cannot say that a piece by Xenakis is objectively better or more advanced from an aesthetical or artistic point of view than a piece by Bach (Bravo Benard, 2006), even if the math and tools used by the former were more technically advanced. The art stands by itself and is related to its historical context, but the effect that it produces on the listener is what matters, regardless of the tools. I think ideas develop, and composers explore new techniques and tools to bring their ideas to life. Some of those techniques remain, and some are replaced by others over time. I also don't believe in novelty for its own sake, and in any case, novelty is always short lived. In that sense, I don't find it necessary to justify the use of chaos in music as it being particularly novel from a technical or aesthetic point of view. I choose to use it in my music, just like I might choose to use any other tool. In the process of doing so, I may come across elements that are valuable, and that perhaps other people will be inspired to use as well. But I am not suggesting that anybody else should use these tools, unless their aesthetic goals are well served by them. However, the fact that many composers are still interested in these subjects, and that the tools have increasingly made their way into the mainstream, suggests to me that there is some value in continuing to explore them, both for synthesis and for composition. And even if not many people are creating music specifically about chaos these days or with it as its main topic, I believe that these systems are increasingly present in the toolbox of contemporary electroacoustic composers in different ways, even if only through the use of control signal generation for synthesis, to give but one example.

One important element that I think has changed since composers first explored these ideas is the accessibility of computers and tools to implement complex systems. Through software such as Max and SuperCollider, or through virtual modular systems such as Voltage Modular and VCV Rack, it is very easy to implement chaotic systems by just choosing the right function of module, and to experiment with these ideas without having to necessarily focus on them specifically. Furthermore, because of the modularity of these systems, it is possible to explore meta-systems where many subunits that implement chaotic systems interact, and to quickly reconfigure these systems on the fly simply by changing the connections of the system. I believe that this availability will result in a wider use of dynamical systems in music, and that perhaps some new sonic possibilities will come about as a result.

The Chaos Studies represent an attempt, still in its early stages, to systematically explore some specific elements of the use of chaotic systems in music, with the intention that this process will inform my musical practice in the application of these tools, and about composing in general with the type of noisy structures they produce. Some of the fruits of that have already made their way into later pieces in the portfolio. The exploration of the type of dynamical systems that one can create for live performance is another subject that I believe can be useful for future work.

Developing My Own Chaos Modules

I was interested in developing my own tools, rather than simply using available ones, because, aside from the financial incentives already mentioned, this offered me greater flexibility and allowed me to find my own way of doing things and starting from scratch, rather than relying on implementations that were developed by other people, with their own design choices and limitations. I also found it both challenging and exciting to be able to implement a multitude of chaotic functions, and exploring the differences in the output they could produce.

Implementing these systems from scratch also allowed me to study them more thoroughly, as this was necessary to implement the math correctly and ensure that they functioned as intended, especially since they were being released commercially. There were also reasons why the implementation as voltage-controlled modules was particularly appealing. As much as I love the flexibility of coding and of tools like *SuperCollider* and *Kyma*, sometimes I find it useful to have a certain level of separation between, on the one hand the technical elements such as the math and the syntax of the language, and on the other the creative flow and playfulness when exploring the tools musically.

Having these tools as modules is very useful, because it gives me an easy and reliable way to explore these non-linear systems by simply tweaking knobs, without having to worry at that moment about coding or signal flow within the system. The modules also implement some safety measures to prevent the systems from blowing up and producing completely out of range values, as can sometimes happen with some chaotic systems. Being able to control the modules through voltage signals is also extremely useful, as it makes it easy to explore the behavior of the system as its parameters change over time, and allowing for easy experimentation. The system can be completely reconfigured by just repatching a few cables, and one doesn't even have to worry about whether the connections make sense or not, but rather just explore the results playfully by ear. Voltage control also makes it easy to make more complex systems and networks by interconnecting multiple chaos modules and having them affect each other in complex networks. This can be done in seconds by combining modules, without having to worry about the underlying code or math. This would be very difficult, if not impossible, to do with most commercial software, very expensive to do with hardware modules, and very challenging to accomplish with code when the interconnections become really complex. So a virtual modular platform like Voltage Modular proved to be ideal for me to experiment with these systems.

Analog Vs Digital

One question that might arise in the use of computer implementations of non-linear dynamical systems is whether their chaotic properties are truly equivalent to those of chaotic analog systems. Since digital systems are deterministic, does that mean their behavior will be strictly repeatable every time we run the system? It is important to remember that chaotic systems are themselves mathematically deterministic, but because of sensitivity to initial conditions their behavior is difficult to predict, and from a perceptual level it can even appear random under some circumstances.

In analog systems, small fluctuations in voltage and minute differences in component properties introduce additional sources of uncertainty. These physical factors can cause slight variations in system behavior, even under seemingly identical conditions. In digital implementations, however, chaotic systems behave similarly, though not due to physical randomness. Instead, this variability arises from the sensitivity to initial conditions — a hallmark of chaotic systems — combined with the finite numerical precision of computers.

As a result, even if we run the same digital system with seemingly identical initial conditions, tiny rounding errors in the numerical representation of values can accumulate and amplify over time, causing the system's trajectory to diverge. The overall macroscopic behavior will remain similar, but the precise path the system takes may differ with each run.[7] Furthermore,

[7] See Gleick (1987) and Lorenz (1993) for a discussion of this phenomenon.

the segment of the trajectory of the system that we will encounter at a given moment when using the digital model will inevitably vary as well.

Digital systems also offer some unique advantages: we can deliberately inject randomness (e.g., through the use of random seeds) to increase variability –when the system is first initialized or at any desired point later on, save and recall parameter presets, and systematically explore parameter spaces through automation. Additionally, digital systems make it easier to explore more complex configurations of interconnected systems, as we can add as many copies of a given chaotic generator as we desire, not restricted by the limitations of the analog systems and modules that we may have at our disposal. These capabilities make digital systems powerful tools for investigating the boundary between order and chaos — possibilities that in some cases would be much harder to achieve with purely analog implementations. In this sense, digital implementations are not inherently inferior to analog ones; instead, they provide complementary methods of exploration, each with its own creative potential and advantages.

Sonification and Music

One important point that I would like to emphasize is that the goal of making these modules and using non-linear dynamical systems in my music was not to model specific chaotic systems scientifically or for strict sonification purposes. The aim was instead to take these systems and use them as starting points for sonic exploration, in order to facilitate the production of rich timbres and interesting sonic behavior that would be difficult to achieve with more conventional methods. The dynamical systems are implemented as modules, but they are only the building blocks and tools to be used for creating music. The music is obviously not what the modules output, but rather what the composer eventually does with that output, guided by other formal and aesthetic criteria. The modules are then tools for creating data-driven music.

When we use data from physical phenomena in music, we often have to deal with the expectations and associations that tend to accompany this practice, and with the distinction between sonification and music, and whether or not the music maintains any of the attributes associated with the original context of the data. I find it extremely problematic when people use the sonification of data sets coming from a given phenomenon, either through strict mapping or as part of composed musical works, and then claim that the results are what that phenomenon "sounds like", be it the stars, chaos, black holes, or anything. Unfortunately this is something that I have encountered countless times over the years in popular media, which is why I decided to mention it here.[8] In academic circles, I've often heard similarly misleading assertions — or the opposite, with pieces like Xenakis's *Pithoprakta* being informally labeled as 'sonification pieces.' This isn't too far from calling Vivaldi's *Four Seasons* a sonification as well. And while both draw inspiration from natural phenomena in different ways, using such terminology blurs the distinction between artistic interpretation and pure sonification, ultimately obscuring the conversation.

Even going back to the old Greek concept of the Music of the Spheres (James, 1993), be it as metaphor or as attempts to recreate physical phenomena or mathematical relationships through sound, these concepts and procedures can influence and inform artistic practice and philosophy, but the application of these ideas does not automatically result in artistic works,

---

[8] See for example "What do stars sound like?" at pbs.org (https://shorturl.at/ECuqp), "Symphony of Stars" at nasa.gov (https://shorturl.at/y6MZ6), or the YouTube videos "What space sounds like" (https://shorturl.at/lcbat) and "The sound of chaos" (https://shorturl.at/ks0KV). Links accessed on August 28th, 2024.

let alone in novel or aesthetically successful ones, and the works themselves are not in any way objective representations of the phenomena. This may seem like an obvious point that has been discussed countless times in the past, but I think it is important to keep it in mind in the context of this portfolio, especially regarding my artistic intentions and research. Sonification can be very useful for scientific and didactical purposes, as it can help us understand a phenomenon better, or even to experience certain aspects of its behavior. But it is misleading to claim that a sonification is what a certain phenomenon sounds like. After all, the phenomena don't sound like anything by themselves – otherwise we wouldn't need to sonify them and we could just listen to them directly. Whatever we choose to do with the data we take from a data set or generator –even if read directly as sample values in a digital system for example– is already a creative act that involves personal choices in the mapping of parameters, whether it be for aesthetic or representational purposes. This is especially true when the material is developed into more elaborate musical structures and with specific aesthetic goals, rather than simply for the purpose of sonifying the data to understand a phenomenon better in a scientific way.

It is important to distinguish between the creative act of composing and the development of these data-driven tools as sound generators, even if both ultimately contribute to the creative process, and to also differentiate the intent and goals of musical works from scientific or illustrative sonifications. As Carla Scaletti has argued, sonification ≠ music, but doing data sonification can change the way we think about data, mapping, and sound synthesis and control, but also about music itself. Music is also always a form of sonification, even when it doesn't directly map data from nature, as there are still other mappings taking place in the process that results in sound, and even in the perception of music. (Scaletti, 2004). But it is misleading to simply call music with data-driven elements sonification.

Miladl Khosravi Mardakheh and Scott Wilson have provided a useful framework for discussing the subject of artistic data sonification using a strata-based approach (Khosravi Mardakheh & Wilson 2022). They propose three types of artistic data sonification:

- **Generative:** Uses data purely as a tool to create new sounds, often without concern for the data's original meaning, similar to algorithmic composition.
- **Allusive:** Maps data to sound in ways that symbolically reference the source material, adding interpretive layers without strict scientific accuracy.
- **Curatorial:** Uses sonification as a way to present data as a perceptual experience, balancing artistic expression with preserving the data's structure.

Using this framework, I would consider my musical works in the portfolio to fall mostly under the generative category, in that they use data as a starting point, but without making explicit reference to the source of the data or pretending to accurately represent the phenomena that produced it –in this case the non-linear dynamical systems. Some works would also fall to some extent under the allusive category, such as the *Chaos Studies* and *Bullet with Butterfly Wings*, as these make direct reference to the chaotic sources in their titles and program notes, making the listener aware of this connection. I do not consider any of the works in the portfolio to fall under the category of curatorial. My focus was on artistic creation rather than mathematically accurate sonification for illustrative or scientific purposes in any way.

My music is not a sonification of chaos, nor does it pretend to be what these systems sound like in any way. Chaotic systems can be useful models for music, but in the end I see them more as just tools for lively non-repetitive modulation, allowing us to move between order and randomness in interesting ways, and as powerful generators for noise-rich material capable of producing a vast range of timbral textures. But their output is just a starting point.

I think this is often the case with non-standard techniques for sound synthesis, and for compositional ideas in general.

Conceptual Ideas in Music

When examining Xenakis's use of dynamic stochastic synthesis (Xenakis, 1992) –an important historical reference in the field of non-standard synthesis and data-driven music– we encounter what could perhaps seem as a discrepancy between some elements of his initial conception of the technique and its actual application in practice. Xenakis described the technique as a means of directly synthesizing a waveform — theoretically, any waveform, as suggested when he says that "following these principles, the whole gamut of music past and present can be approached" — yet in practice, he treated it more as a sound generator or instrument. The material produced through stochastic synthesis was often layered with sounds from other sources or multiple instances of itself, combined either intuitively or through additional stochastic procedural methods.

In *La Légende d'Eer* (1977), widely regarded as his electroacoustic masterwork, Xenakis incorporated material generated with dynamic stochastic synthesis alongside a variety of other sound sources and synthesis techniques. Later on, the last two electroacoustic pieces that he officially completed, *GENDY3* (1991) and *S.709 (*1994), were produced using sounds exclusively generated through stochastic synthesis. In those pieces he arranged multiple layers of synthesized material overlapping in time (Serra, 1993; Hoffmann, 1996). These layers were structured through additional stochastic processes that were implemented into his Gendyn program to carry out the selection of meso-level material, applying similar principles at different structural levels of the composition –a recursive approach that aligns with Xenakis's broader compositional philosophy and that is present throughout his works.

While this method is entirely valid artistically, in some sense it could be said to diverge somewhat from the original philosophical idea of synthesizing the final sound wave directly through a computational process that starts "from a probabilistic waveform" (Xenakis, 1992, pg. 289). A meta-process is applied for the selection of the layers, even if it is a related process sharing similar stochastic principles, but this organization can be seen as composition rather than as pure synthesis. Of course, it could be argued that the meta-process is itself the actual process, and that Xenakis blurs the distinction between the different structural levels in this way, as was part of his conceptual intention. But the introduction of layered voices and the use of additional processes means that the resulting sound is shaped not solely by the original stochastic synthesis itself, but also by higher-level compositional decisions, even if these were algorithmic. Furthermore, Xenakis always maintained a flexible approach when it came to the final compositional decisions in his work. What we hear in the end is not a purely synthesized waveform but a complex, multi-layered sonic construction that has been shaped at multiple levels. And while dynamic stochastic synthesis can theoretically create an enormous variety of sounds, including ones that might resemble existing instruments or noises, its real power lies in its ability to create sonic phenomena that would be practically impossible to achieve through traditional means. In this sense, Xenakis wasn't aiming to cover the entire universe of possible sound, but rather to explore sound as a space of infinite potential, where new forms and behaviors could emerge through randomness and probability. But the original idea of synthesizing a waveform directly from mathematical functions through stochastic processes opened the door for him to a new world of sonic discoveries.

I think this situation is not rare. Conceptual ideas in sound synthesis and composition can be useful to direct our progress and push us forward, but in the end the results are rarely exactly what we set out to do. No technique or procedure is really capable of producing any sound we can imagine in reality, but along the way we may discover many sounds that we hadn't imagined. It may be the discovery that happens in the process that is the most fruitful.[9] As appealing as it is to think that we can use a certain procedure to realize an entire composition, in reality musical possibilities are just too vast for us to cover them completely using such methods, and much more interesting results can be obtained when we use intuition to structure music in addition to whatever formal procedures or techniques we may be employing. I believe that is also what made Xenakis's music so powerful, as he was never dogmatic about the implementation of his ideas, and always put the sonic results first. This is why I see the use of chaotic systems, even when forming a central part of my practice, as only a starting point for musical creation. The pieces still need to be composed, but it is potentially a very powerful starting point that offers exciting possibilities, even today, several decades after composers started exploring these ideas in sound.

[9] When dealing with conceptual ideas in sound synthesis and composition, I am reminded of the take on utopia by the filmmaker Fernando Birri which was popularized by Eduardo Galeano and I have summarized in English as follows: "Utopia lies always on the horizon. When I move two steps closer, it moves two steps farther away. I move ten steps closer, and it moves ten steps farther away. As I walk, I make my journey, but the distance to the horizon remains ever greater. So, what is the purpose of utopia? It is precisely that: to cause us to walk." Galeano recounts this story in his book "Las Palabras Andantes" (Galeano, 1993), and in many interviews over the years (see for example this video on YouTube: https://shorturl.at/QNK2N, accessed on August 28th, 2024).

Some Considerations on Implementation

While the mathematical equations were implemented carefully to reproduce many well studied non-linear dynamical systems capable of producing chaotic behavior, I also allowed myself complete free range to explore what happens when those equations are modified in certain ways, or put under arbitrary artificial constraints. This was also necessary in some cases to make sure that the output was stable under all conditions and ensure that the modules wouldn't crash the software, for example by producing extremely large numbers as the output of the system approaches infinity under certain conditions. This may in some cases violate the canonical implementation of some of the systems, but it can also be used to produce interesting and more musically useful behavior.

In my view, there is nothing sacred about these systems or the math behind them. They are only tools for music that can be modified according to our musical needs, just like an instrument maker may tweak their design in order to get better sounding instruments. And the main goal as artists is not to study chaotic behavior, but rather to create music.

The modules can still be used to faithfully reproduce the behavior of chaotic systems in most cases, and even for strict sonification if desired, especially if the parameters are kept constant over time and within specific ranges. But I see this as a specific use case rather than as the norm, and in the implementation of the modules I tried to go beyond these constraints.

One example of this is the implementation of the capping function in some modules. This keeps the values, not just of the output, but also of the system internally, within certain boundaries. I also discovered that doing this could produce some very interesting and unexpected behavior, such as in the Tinkerbell system, which I implemented in a module I ended up calling *Tinkerbell on a Leash*, in allusion to the restricting changes I made to its implementation. I discovered that by limiting the internal values, the system became stable enough to be used safely, but the modifications also produced some fascinating sonic side effects when the system parameters were modified over time. I also gave appropriate names to some of the other modules to reflect this capping, such as the *Constrained Ikeda Map*. Instead of simply capping the values, I made it possible to also control the capping range through knobs and voltage control, which I found very musically useful. In this sense, it is important to remember that when designing tools for synthesis, there is no right or wrong answer, but rather only good and bad choices. If a module with faulty math produces interesting sonic results, I find that to be more useful than one that follows the canonical description of a system faithfully, but that doesn't produce interesting sounds. And because these tools are used to produce music, and thus beauty rather than truth, a mistake can be a happy accident, and we don't have to worry about whether or not that invalidates our scientific conclusions. If it sounds good and it works well, then it is useful. So I welcomed happy accidents, and embraced the beauty of glitches and errors in my modules.

Another design choice was the addition of the Inject button and trigger input to reset a module. This introduces new random values into the system, replacing the running ones and setting the system on a new path. Because of the importance of sensitivity to initial conditions in chaotic systems, this can result in the output behaving quite differently when the system is reset, thus creating different paths through the output space of the module. Depending on the system and parameters, the system can quickly gravitate to an attractor and settle again into periodic behavior, or it can behave completely differently. As this can be triggered through voltage as well, it allows for rhythmical resetting of the system with other signals if desired.

Scaling of the output was also built directly into the modules for convenience. This ensures that the voltage ranges the module outputs are appropriate for the modular environment, but it also makes it easy to scale and offset those values without the need for additional modules.

This is useful because the range of output values of the system can vary greatly, and may not be centered around the same value for the different outputs in some modules and under some conditions. The scaling options make it easy to adjust the ranges by ear, directly from the module, and these ranges can also be controlled or modulated by other voltage signals. See Appendix A for a list of the modules implemented in Voltage Modular so far. [10]

Spatialization and The Use of Ambisonics

Space has always played an important role in my compositional practice, even dating back to my earliest instrumental works. However, when working with acousmatic music, where one can more easily bypass some of the limitations and constraints of physical instruments and performers and their position in space, I am particularly attracted to the possibilities that composing sound in three dimensional space can afford. This setup also aligns well my aesthetic goals, and makes it possible to place the listener in an immersive sound world. And because my music deals with timbrally-rich sonic structures and a high density of material, specialization also helps to differentiate the multiple layers and to create spatial counterpoint. For this reason, I have adopted Ambisonics[11] in my creative practice, as I find this to be a very useful and flexible standard for immersive audio, and one that can easily be adapted to multiple listening conditions and venues, due to its speaker-agnostic nature. Most of the pieces in the portfolio were created using a higher-order Ambisonics setup, subsequently rendered to stereo and binaural formats for listening with conventional systems. But the pieces are conceived to be performed ideally in a multi-channel 3D setup, such as the BEAST system at the University of Birmingham.

[10] The list is still growing, but only some of these modules have been released commercially so far.
[11] See Zolner and Frank (1999) for more information on the subject of Ambisonics.

Many of the works in the portfolio have already been presented in multi-channel setups at conferences and festivals such as the International Computer Music Conference, Australasian Computer Music Conference, New York City Electroacoustic Music Festival, BEAST FEaST, Sonorities Belfast, SEAMUS, and the Foro de Música Nueva Manuel Enriquez.

Upon request, the author can provide versions of the works in the portfolio in up to 7th-order Ambisonics format.

COMPOSITIONS

1. CHAOS STUDIES

"The more constraints one imposes, the more one frees one's self. And the arbitrariness of the constraint serves only to obtain precision of execution."
— Igor Stravinsky

This is a series of short works exploring the use of chaotic generators for sound synthesis.

Having implemented different non-linear dynamical systems capable of producing chaotic behavior, as virtual modules in the Voltage Modular platform, I set out to create a series of relatively simple pieces made exclusively from audio material that was produced through the use of these modules.

In addition to my interest in exploring the use of non-linear dynamical systems for non-standard sound synthesis, this was also a way for me to test the usefulness of the modules themselves for music creation in a very direct way, and with very deliberate constraints. It also became a compositional exercise that forced me to come up with material using only the specific tools that I had chosen at the onset. I often find it challenging to make decisions when composing, given the endless choices available to produce material, as well as the many tools that can be used for sound generation and processing in electroacoustic music. This can sometimes result in a sort of paralysis that makes it difficult to move forward. By setting very specific constraints, such as the selection of certain tools, along with a specific compositional system or set of rules, it can sometimes be easier to be creative within the boundaries of what those constraints allow. This process can also be helpful in exploring the tools and techniques that I was developing, in the context of shorter pieces that focus on limited ideas. The knowledge gathered through this process can then be used to refine both the tools themselves and the compositional techniques for which they are used, which in turn can be applied later to more extended works.

I decided to limit my tools to single patches created in Voltage Modular, using my chaotic modules directly for sound generation, or for controlling parameters of other oscillators and filters. The patches were initially created through playful exploration, and once I settled on them, I set out to produce the sound material I would use for each study, limiting myself to that specific patch as the only sound source, and going back to it to produce the material I needed as the piece developed. In some cases I had no pre-planned musical ideas before I started the piece, but in others I was exploring specific ideas that I thought chaotic generators could be useful for, such as the organization of granular structures in Study No2, or the additive effect of multiple layers of noise with different timbral characteristics.

The first five studies of the series are included in this portfolio, which were produced between 2020 and 2022. After this period I have created many other suitable patches that I might use for composing more of these studies in the future in a similar setup, as well as for live performance. For the works that I composed immediately after these studies, I abandoned these constraints and focused more on imagination and intuition to try to achieve my musical objectives, using the chaotic generators only as part of my toolset, and working in the way that I normally would when composing electroacoustic music. But the studies were useful in exploring some of the sound possibilities of the modules, as well as dealing with some of their limitations and challenges in using the type of sonic material that they produce, and they helped me to find the direction for my later work.

All the studies were produced in 3rd order Ambisonics, but unlike in the later pieces, spatialization plays a relatively minor role in the studies, and it is used mostly to achieve separation of different voices and layers of material.

Study No. 1

Duration: 4:00

This piece uses a patch consisting of a Rössler Attractor module driving multiple saw oscillators. This module is also connected to itself in a feedback loop, affecting some of its own system parameters through voltage control. A Logistic Map module is used to modulate the rate of the clock of the Rössler system. The output of the oscillators is fed into two ladder filters and their cutoff frequency is in turn controlled by the Rössler module as well. The patch also contains a random voltage generator that produces slowly changing values, and this affects the B parameter of the Rössler system, producing gradual changes in its state over time. The patch is capable of generating a wide range of sounds, going from pulses, to noise textures, to clouds of pitched notes.

Fig. 1 – Patch used for Study No. 1

The Rössler Attractor implements a system of three non-linear ordinary differential equations, and was originally studied by Otto Rössler in the 1970s, and implemented as follows:

$$dx = (-y - z) * dT$$

$$dy = (x + a * y) * dT$$

$$dz = (b + z * (x - c)) * dT$$

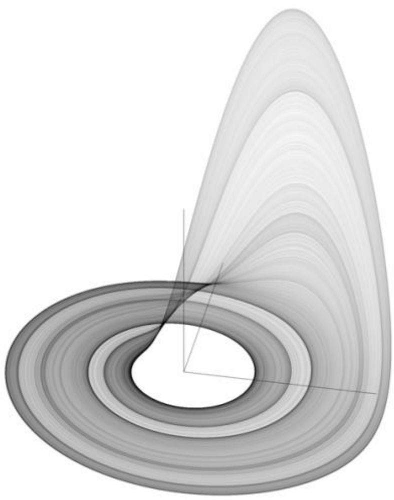


Fig. 2 – A 3D plot of the Rössler Attractor

Fig. 3 – A plot of the X and Y values produced by the Rössler Attractor module.

The logistic map is a one-dimensional discrete-time map, and it is one of the simplest ways to produce chaotic behavior. It has been used to model many phenomena, such as animal population growth. After Edward Lorenz used it in his work in the 1960s, it was popularized by the biologist Robert May in a 1976 paper where he explained how complex behavior can arise from very simple mathematical models (May, 1976). It uses a first order difference equation to calculate discrete time steps, as defined by the following equation:

$$X_{n+1} = rX_n(1 - X_n)$$

Where X_n is a number between zero and one, and r is the single parameter controlling the behavior of the system. This process produces a pattern of recursive bifurcations as the value of r increases between 3 and 4. In the module, r is labeled as λ, following convention.

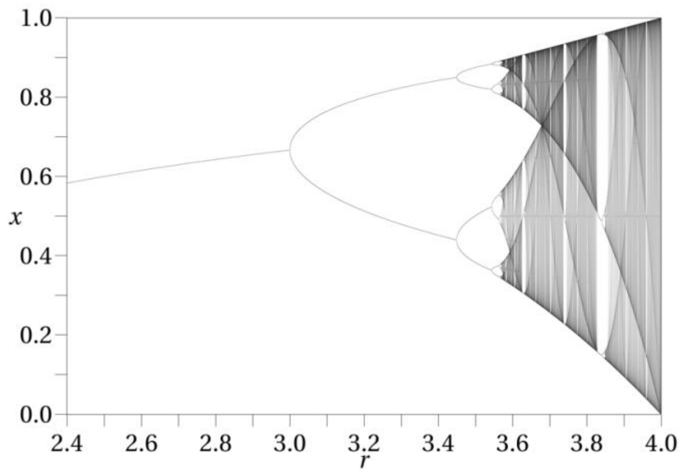


Fig. 4 – The bifurcation patterns of the logistic map

In the implementation of the modules, a clock controls the rate of values produced by the system. By interconnecting multiple modules, one chaotic system can be used to control the rate of evolution of the second one, which can produce interesting and sometimes surprising behavior.

The piece starts with a block of noise, and other layers are added shortly after, some with pulsating inner rhythms, and others with breaks in between bursts of noise. There are also clouds of high oscillator sounds, and noise that resembles scraping on a rough surface. The multiple layers are combined and placed at different points in the virtual sound field, with small movement in space and changes in density, creating a counterpoint of noise layers. The overall spectrum remains quite saturated throughout, but as the piece unfolds, the inner movement of the layers slows down, and some of the voices freeze into static textures and then fade away. The pulsating rhythms of some of the voices accelerate and slow down as the clock rates of the generators vary, affected by the logistic map module and sequences of random voltages. This causes the multiple streams to run at different speeds, dissolving into each other and eventually fading into the background, and into silence as the piece comes to an end.

Study No. 2

Duration: 4:43

One interesting aspect of chaotic systems is that they produce a particular kind of behavior that can go from seemingly random to very clearly repetitive structures. This happens as the values produced by the system are drawn towards patterns governed by the system's attractors. The output values can therefore fall into specific quasi-cyclical patterns, or suddenly break away into different behavior when we change the values of the parameters in the system. This type of behavior can be used to control particle systems at the macro level, such as in granular synthesis. This is the main idea behind the second study. The piece is made up of granular clouds that are produced by using the output of chaotic generators to control the frequency of oscillators, with a fast clock running the system to produce quickly changing values that are perceived as clouds of fast notes. As we change the behavior of the system by adjusting its parameters, we hear different clouds that settle into specific ranges, or that follow patterns that repeat with small variations but with a great deal of similarity at the meso level. This is interesting because it provides a middle ground between complete randomness and predictable repeating patterns, giving us a sort of continuum between the two that we can explore musically, and producing perceptually interesting behavior.

In Study No. 2, several of these clouds are combined and interact with each other as the piece develops, resulting in slowly evolving granular textures. Towards the end of the piece, the clouds transform into textures with less clear pitch content, as the rate of change increases and the range moves to a lower register, resulting in wind-like sounds that arise from artifacts in the frequency modulation of the oscillators. The original pitched textures return shortly after, and as the piece ends we hear a cloud that, while slowing down, turns into a sort of melody that for a moment reveals its inner structure and then fades away, while another fast moving high cloud remains and then dies off as well. The most important elements that the piece explores are the emergent behavior that is perceived as the content of the clouds changes, and the subtle but perceptible differences in the inner structures of the clouds as they develop over time.

The generators used for this piece were the cubic map and the discrete laser map. These are one-parameter discrete maps that produce bifurcation patterns. They can be seen as variations of the logistic map that produce equivalent behavior, namely recursive patterns of bifurcations. I chose these modules because I found their behavior to be easier to control and to keep within the boundaries of what I was trying to achieve musically through the small differences of structure in the granular clouds.

Fig. 5 – The patch for Study No. 2

At a certain level, the material in this piece bares some obvious similarities with the classic granular pieces from the 1980s by Barry Truax, such as *Riverrun* and *The Wings of Nike*, as do most pieces using purely granular textures. However, unlike those works, this piece is just a short study that only explores some basic ideas, and doesn't go very far in developing them compositionally. It is simply an initial proof of concept, but I think that the use of chaotic generators for controlling macro behavior in particle systems in this way has very promising potential for future development, and this study was just a short exploration of that idea. I found the results encouraging, and I plan to develop these techniques further in future work, studying the different types of clouds and macro behavior that can be produce by different chaotic systems and their attractors, and how perceptually relevant these differences can be for the organization of material in musical creation.

Study No. 3

Duration: 2:29

This piece is a very simple drone study made up of a few voices produced with a chaotic patch. The patch generates tones with a rich spectrum and some micro movement, and as the layers interact in the virtual sound field, we get different pulsations and resulting timbres. The output of the main chaos module, a Hopalong Map, is fed into a glitchy filter, the parameters of which are also controlled by the same module. Random values are periodically fed to the system to change its state. There is also a second Hopalong module that is interconnected with the first one, and its output is also used to modulate the rate of the external clock driving both modules. Panning is controlled by the Hopalong modules as well, using the X – Y signal, which outputs the difference between the X and Y values of the system at each time step. The sounds for this study were generated directly by the output of the modules, additionally processed through filters. But there were no additional oscillators used in this patch. The piece is a simple exploration of the noisy textures and timbres that can be produced through a system of intermodulated chaotic oscillators used directly for sound synthesis, and the micro-fluctuations in the signals that result from this process.

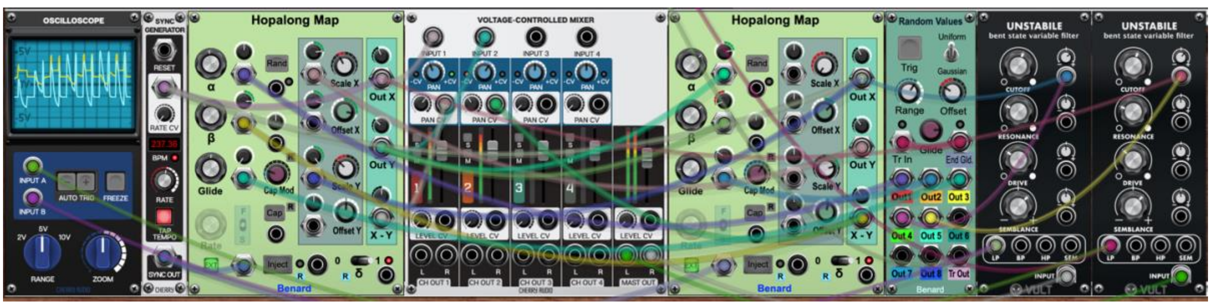


Fig. 6 – Study No. 3 Patch

The Hopalong map is a two-parameter discrete system, implemented in pseudocode as:

```
xNew = yOld - signum(xOld) * sqrt(abs(beta * xOld - delta));

yNew = alpha - xOld;
```

Study No. 4

Duration: 6:09

This piece was produced using a simple patch consisting of a De Jong attractor modulating the frequency of two square wave oscillators with its X and Y outputs. A comb filter processes the output of the oscillators, and the filter's output is itself routed back to the De Jong attractor module to affect its parameters. This creates a feedback network capable of producing complex and constantly changing behavior, fluctuating between pulses and noise textures.

Fig. 7 – Patch for Study No. 4

The De Jong attractor is a two dimensional, four parameter discrete system of the form:

$$\mathbf{x_{t+1} = \sin(a * y_t) - \cos(b * x_t)}$$

$$\mathbf{y_{t+1} = \sin(c * x_t) - \cos(d * y_t)}$$

When the clock is run slowly, the patch produces different pulsating patterns in the oscillator with each new value. This is how the piece opens, with pairs of rhythmic pulses, coming from the X and Y outputs of the module, placed on opposite sides of the sound field and changing periodically. This type of activity continues throughout the first part of the piece, alternating between different rates. With faster clock settings, the patch can produce stable tones, which start appearing later in the piece, where we get a juxtaposition of pulses and fast-moving noisy textures, along with occasional short stable tones. Noisy clouds become more prominent as the piece develops, which are produced as the different parameters of the system are altered and the speed of the system's clock is increased. The overall texture gets denser as more voices are added, consisting of pulses, tones and noise clouds, and these 3 elements continue interacting in counterpoint for the remainder of the piece, with sudden changes in density, pace, and spatial position of the voices. The piece is very simple and repetitive, but it captures the type of evolving behavior that can be produced through chaotic systems, and I imagine it as a sort of inner dialog of such a feedback system as it explores its own voice and responds to human input. This behavior is also something that I am interested in exploring in the future in a live performance setting. The relative unpredictability of such systems, and how their behavior can change drastically as a result of small changes to their parameters can present interesting challenges and possibilities to be explored in real time in a live performance setting.

Study No. 5

Duration: 4:40

Similar to Study No. 3, this piece was produced with a patch consisting of two interconnected Hopalong Map modules, but in this case they were used to modulate the frequency of sine oscillators, rather than producing sound directly. The Hopalong modules in the patch have a square oscillator that can be selected as external clock, but it is passed through a Bernoulli Gate module, which stochastically allows only a percentage of the pulses through, resulting in a non-steady clock that can produce interesting rhythmic effects and sounds with different inner rhythms compared to the internal clock. Some of the sounds also make use of the capping feature of the module, which restricts the values output by the system to specific ranges before feeding them back into the system. This can produce contrasting results, especially as the value of the cap knob (i.e. the ceiling of the values used in the system) is varied, and can also prevent the system from becoming unstable under certain parameter settings. Several presets of the patch were made, exploring its possibilities, and these were then used to generate the different layers of sound material.

Fig. 8 – Patch for Study No. 5

The piece starts with a low pulsating sound, and multiple layers of relatively quiet noise are gradually added to the texture. Scream-like and crackling textures are introduced later, along with occasional stable tones that quickly break apart, exploring the different types of sounds produced by the patch and weaving them into dense textures. The work continues with pulsating rhythms and layers of noise, with only some short breaks in activity, where single voices emerge into the foreground for a moment in rhythmic gestures, quickly being swallowed back by a wall of noise that keeps growing thicker as other layers and harsher timbres are added. Eventually the noise dissipates and gives way to quieter pulsating low textures towards the end, as if the system collapsed onto itself and faded away, or its substance escaped through the very holes that the noise pierced.

Conclusion

These pieces were useful in exploring some of the possibilities of the chaos modules I developed. In the end the studies were as much about the process of designing small individual patches and using them to produce a variety of sounds for pieces, as they were about exploring the modules themselves. Looking back at this work some time later, I feel that it was useful in discovering some possibilities and limitations of the tools, and in suggesting possible directions for future work that might be promising, and some aspects that are not so specific to these modules but rather to working with noise and non-standard synthesis techniques in general, and how one can go about composing with such material. Some of these points I explored in later works, while others I would like to revisit and develop in the future. I think the process of setting up very specific constraints and making short works exploring them is something that I may want to do more of, perhaps expanding on this series of studies. I also found some value in the idea of forcing myself to explore sounds, but with the condition that it has to result in some sort of composition, even if it is a short one, as in the past I have very often spent time playing with sound and coming up with interesting material and ideas that are then lost and forgotten. Perhaps a healthy balance between playful exploration and some constraints for ensuring that the results make their way to compositions is what I would find ideal. But in the end I am more interested in picking up and refining the most appealing techniques and ideas that I encounter in the process of making such short pieces, and incorporating them into larger and more artistically ambitious works. From a compositional point of view, the experience also made me think more explicitly about form, and this is an aspect that I would definitely want to pay more attention to when I continue the series, including designing some constraints on form into the pieces as well, as opposed to only assembling the material in an intuitive and unplanned way.

The process of designing patches for entire pieces is also something that I would like to explore more for live performance, especially in the context of chaotic systems that are somewhat unpredictable and allow for interesting interaction between the system and the performer. The kinds of patches that I would design for such situations would perhaps be quite different, but I am very drawn to the idea of musical experiences that can only be produced in a live setting as one interacts with a system and its somewhat unpredictable emergent behavior.

Finally, from the technological development and tool design point of view, working on these studies was also very valuable, and the experience will inform my process and design choices for future module and software development.

2. VERTIGO

Fixed media acousmatic work
Year of composition: 2020
Duration: 18:48
Format: 3rd order Ambisonics

Overview

This is a fixed media work created with computer-generated sound sources exclusively, using my own software modules and patches. It consists of string-like beating clusters that move slowly, and harsh noise sounds in dense textures. The sounds are arranged in 3D space, rendered in 3rd order Ambisonics.

Compositional Ideas and Process

One day in the spring of 2020, during the isolation of the pandemic and at the time when I had started generating the sound material for this piece, I found myself cleaning my kitchen while listening to music on headphones. During a particular passage of an instrumental piece – *Searching*, by guitarist Joe Satriani – that consists of fast dizzying glissando lines on the electric guitar produced with a whammy pedal, I turned my head and suddenly everything around me started spinning. I dropped to the floor, thinking that it would soon pass, only to discover that every time I opened my eyes, everything around me kept spinning and I would become completely nauseated. After vomiting multiple times and lying on the floor for a long time completely unable to move or get up, I eventually managed to very slowly crawl to the next room to grab my phone and call an ambulance. When I arrived at the hospital and was told the time, I realized that what I had perceived as a couple of hours lying on the floor had in fact been close to six hours, and I was shocked at how my perception of time had been altered being in that condition and situation. I spent the next two days in the hospital, unable to walk or even open my eyes for the first several hours. But after being examined, nobody was able to tell me exactly what had caused the problem. The doctors simply called it a case of vertigo. The symptoms gradually went away and I eventually recovered completely and was sent home. But the memory of the incident, which in those moments felt like falling outside of my own body and not being able to find my way back, and the fear of the symptoms suddenly reappearing, stayed with me for a long time, and I kept wondering if the episode had at least in part been triggered by the sounds I was listening to when it happened.

This work is not intended to be programmatic and does not try to recreate the specific feelings of dizziness of that episode, but the experience inspired me to try to evoke some of the sense of confusion and disorientation that I felt at the time, especially in the context of being immersed in sound when it was triggered, and how such a situation can affect our overall perception and sense of balance, as well as the initial horror I felt when it happened and the awareness of how fragile life and consciousness can be, where even the ability to perceive time and space and everything around us clearly, can suddenly become compromised when something in our body fails. The piece uses clusters of beating sounds and thick walls of noise, sometimes producing a feeling of discomfort, as if being assaulted by sound, and at the same time somehow drawn to some aspect of it that we are unable to fully grasp or untangle from its chaotic surroundings and that we try to resist. This idea and the title also have a connection with the concept of vertigo in Milan Kundera, which he describes as “something other than the fear of falling. It is the voice of emptiness below us which tempts and lures us, it is the desire to fall, against which, terrified, we defend ourselves.” (Kundera, 1999)

All the materials of the piece were generated using my own software modules in Voltage Modular, including several sounds that were created as I was developing and testing these modules for commercial release. These include several noise generators, as well as a graphical oscillator that allows the user to draw a waveform by setting its amplitude points with faders. The latter was used to generate the string-like sounds that occur throughout the piece.

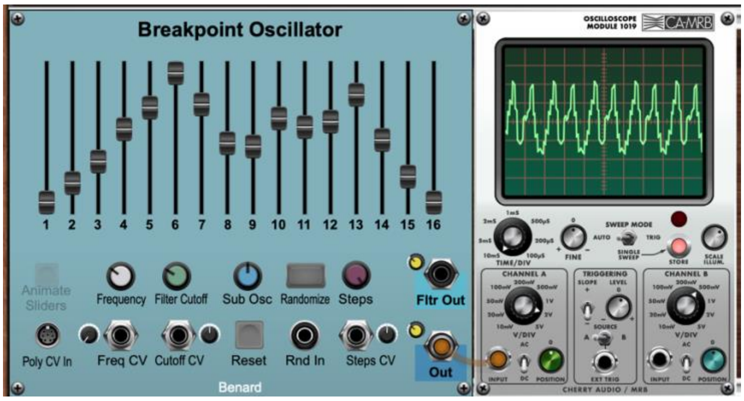


Fig. 9 – The breakpoint oscillator used to generate the string-like sounds.

The work opens with oscillator sounds that slowly change in frequency, producing beating patterns as they do so. This is an element that it shares with some of my old instrumental works, and that I was interested in recreating here with electronic sounds. The graphical oscillator was useful for this, because it allowed me to produce sounds that had instrument-like qualities, but without resembling the sound of string emulations in commercial synthesizers, which I have never found appealing. Other similar voices are gradually added, producing clusters of beating sounds and micro-rhythms. These textures were also doubled with sine tones at specific frequencies to produce the desired timbres and beating patterns, and in some cases the speed of the file playback was also altered slightly over time to produce a similar effect. Multiple breakpoint oscillators were combined, each driven by a Poly LF Noise module, which produces slowly changing continuous random voltages in each of its 16 channels. These voltages were used to set the values of the individual breakpoints, resulting in slowly changing timbers and producing an effect that is similar to that of a dynamic wavefolder.

Fig. 10 – The breakpoint oscillator in a patch, producing slowly moving cluster sounds with varying timbers.

Two minutes into the piece we start hearing other sounds, such as noisy gong-like textures that mix with the original voices, and later glissandi from the oscillators, and short percussive bursts of enveloped noise. Like the string sounds, the electronic percussive material has a connection with one of my previous works as well, and in this sense the piece borrows elements from my own personal past, as if it was coming back in my memory in a moment of confusion and disorientation when for a moment your life flashes before your eyes. The string sounds disappear temporarily as other elements take over, and then return again throughout the piece. The material is gradually expanded into different registers and placed at different points in the virtual sound field as the piece continues. As we enter the second half of the work, a rhythmic sound appears, featuring tones in different registers that make melodic jumps. These sounds are layered upon each other and accompanied by fast moving clouds, creating a chaotic and hectic scene with many sounds happening simultaneously and moving around in the pitch space and virtual sound field, evoking a sense of confusion and disorientation. This material then starts vanishing to once again give way to string sounds that now appear in a lower register, along with some new high granular sounds and clouds of glissandi, evoking the feeling of dizziness that subsides for a moment and then comes back somewhat transformed. The beating high sounds return again towards the end of the piece, first as part of the scene with other low sounds, and later by themselves in the high register as the other sounds fade away and we are once again left with slowly moving clusters similar to the ones that appeared at the beginning of the piece. I think of this moment as the sudden recovery of direction and balance after all the agitation and confusion, where you finally recognize yourself and the world around you as your vision comes back into focus.

Looking back at this piece a few years after I created it, I am not completely satisfied with how some aspects of it turned out, and I may still modify some elements of it in the future, including enhancing some of the spatial elements with techniques I have developed more recently. Some of the restrictions that I placed upon myself regarding the selection of material were perhaps too limiting, and if I were to do the piece over again, I think I would try to use a wider palette of sounds for some of the sections, as well as controlling the density and spectral mix more carefully in order to maintain more clarity. I would also pay more attention to the overall form and how the transitions are structured. But what I learned from working on this piece allowed me to deal with these issues more successfully in later pieces and achieve more satisfying results, so I consider it a valuable learning experience. Listening to it also brings back some of the thoughts I had during that experience and around that time in general, giving it a special meaning for me.

3. BULLETS WITH BUTTERFLY WINGS

Fixed media acousmatic work
Year of composition: 2021
Duration: 15:14
Format: 3rd order ambisonics

Overview

This work was created using computer-generated sound sources exclusively. All the sonic material was produced through the use of a model of the classic Lorenz system of differential equations, either as a 0th order sonification to produce waveforms directly, or to produce control signals that would affect other aspects of synthesis, such as frequency modulation of oscillators and filters.

Compositional Ideas and Process

The Lorenz Attractor module, which I developed as part of my line of chaotic modules for modular synthesis, was at the heart of every patch that was used for sound production for this work, often as part of a complex system of interconnections inside a virtual voltage-controlled modular environment. In some cases, several of these modules were interconnected to affect each other in a feedback loop, as well as interacting with other processing modules and with real-time human control of parameters. Once generated, the resulting sounds were further processed, manipulated, and assembled in an intuitive way, with complete artistic freedom. This work is therefore not a strict sonification of the Lorenz attractor, but rather a musical composition that uses sonification as a tool for sound generation. The aim was not to directly represent the Lorenz system sonically, but rather to produce a musical composition that made use of the chaotic behavior produced by this system, as well as the harsh noise materials that it can generate. The piece could be considered a form of allusive sonification, as mentioned earlier in the discussion about sonification, because it retains some of the context associated with the Lorenz system in its imagery. The title, used here in plural, was taken from the popular 90's rock song by The Smashing Pumpkins, *Bullet With Butterfly Wings*, and was chosen because it captures two interesting metaphorical elements of the piece. The first is the connection with the well-known butterfly image that appears when plotting the Lorenz system with the typical parameter values, as well as the "butterfly effect", which is often used to describe Edward Lorenz's idea that a butterfly flapping its wings in Brazil could potentially produce a tornado in Texas (Lorenz, 1963). The second element is related to the piercing and harsh nature of the sound material, which in some sections, especially towards the end, might resemble a flurry of bullets. I liked the idea of thinking about this piece as sonic bullets being propelled by the butterfly wings of the Lorenz attractor. Additionally, the chorus of the rock song says: "Despite all my rage I am still just a rat in a cage." This line resonated with me, and with the theme of noisy and angry electroacoustic music, in the sense that all this noise can be thrown into the world in all its anger, but in the end I am still just an artist in a studio or performance venue, struggling with the things that make me angry about the world, such as injustice and oppression, and trying to find a way to make an impact and change them in whatever way I can. Music is an expression of those feelings, but it remains necessary to also take action in other more direct ways to deal with those issues and feelings, in order to bring about actual positive change in the world.

The piece starts with harsh noise from the very beginning. This was a deliberate choice, as in many of my previous works I would start from quiet sounds that would eventually build up into noise, so here I wanted to follow a different path and immediately jump right into material of high density and volume. There are two main elements in the first section, consisting of 1)

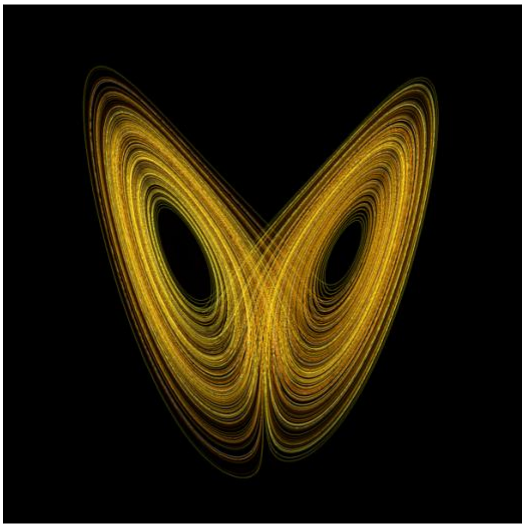


Fig. 11 – The butterfly shape produced by plotting the Lorenz system.

Fig. 12 – A similar plotting of the Lorenz system from the module

continuous harsh noise produced by the output of the Lorenz module directly treated as a sound signal, and 2) low thunder-like sounds that were produced by applying envelopes to similar noise material processed by a lowpass filter. Multiple instances of these sounds interact in counterpoint, and are placed at different points in the virtual sound field, creating very dense textures that resemble thunder and jet engines, with the use of comb filtering. There are also drawn out pitched sounds that appear at times and that are produced by oscillators controlled by the Lorenz module as well. Filtering and equalization are used throughout to shape the sound and help separate the different layers.

Figs. 13, 14 – Two patches using the Lorenz Attractor module

At the four-minute mark, the activity starts to decrease and the low sounds gradually disappear as we transition into a quieter section dominated by high-buzzing tones. Near the 6:30 mark, we enter a brief interlude featuring pulsating low sounds and drones, offering a momentary break from the hectic activity, taking a breath before the momentum picks up again. New sounds emerge and build into much louder, denser textures, characterized by crackling chaotic noises and screaming gestures. This section showcases some of the harsher noise produced by the Lorenz system when its output is used directly for sound synthesis.

As the intensity builds, we encounter high, bird-like sounds and piercing noises that move rapidly in both pitch and space, culminating in a cacophony of chaotic sounds that form the climax of the piece. This is where the metaphor of 'piercing bullets' feels most appropriate. The high bird-like sounds were generated by using the Lorenz system to modulate oscillator frequencies at fast clock speeds, while the piercing noises were created by mixing these with additional Lorenz system noises at similarly high clock speeds.

Following this climax, high percussive sounds return, accompanied by echoes of earlier material. However, aside from brief bursts, the overall density and activity gradually diminish. The piece eventually fades out, leaving only low-register tones and high noisy textures. The final sound is a deep tone that is barely perceptible without a subwoofer. When played in a concert or a proper listening environment, this sound is felt physically more than heard, providing a sensory transition back to silence after the noise. In the mastered version, higher harmonics and a touch of distortion were added to this low sound to make it more perceivable in typical listening conditions.

Fig. 15 – The Lorenz Attractor module used by itself for sound synthesis

Like the Chaos Studies, this work was an interesting exercise in applying a single idea or system, in this case the Lorenz attractor, to generate all the material for the piece. But here it was done in the context of a larger-scale work, and I did not limit myself to a single patch, but rather used a multitude of patches, with the only constraint that they all had to make use of the Lorenz system. After this work, I came to some of the same conclusions as I did with the studies. In general, I find it much more useful to simply add these tools to my repertoire, and use them only when the music and material in question call for it, but driven more by my imagination and always in the service of my creative vision. I am not particularly interested in the application of any tools or ideas for its own sake, but I believe these types of exercises can be valuable in forcing us to explore new directions that we wouldn't normally follow without these constraints, and they allows us to reflect on how we want to use our tools and build a relationship with the process of their development and their application to music creation.[12] The pieces that followed made use of some of these tools whenever I felt it was appropriate, and in general the use of chaotic systems has become an integral part of my repertoire of techniques and sound generators.

[12] This is something that I think was also present in the work of pioneering composers like Xenakis. In my opinion, his greatest works are not the ones where he was simply carrying out a theoretical idea or applying a mathematical process, but rather some of the later, more mature works where he was able to take the knowledge and techniques he developed through that process and applied them to music more intuitively. But his early experiments allowed him to discover his own voice without copying anyone else, and gave him the tools that he would need to compose his greatest works later on.

4. NOWHERE

Fixed media acousmatic work
Year of composition: 2022
Duration: 10:13
Format: 7th order Ambisonics

Overview

This is an electroacoustic work made from sounds produced with different household objects and processed using delays, filters, and spectral techniques. Unlike the previous pieces, this work does not focus on the use of chaotic systems directly, but only employs them seldom for control signals and brief noisy elements.

Compositional Ideas and Process

Like most composers, I have always been fascinated by the sounds around me. From an early age, and probably connected to my neurodivergence, I was highly sensitive to sound, noticing sonic details in my environment that often went unnoticed by others. I frequently grew frustrated by the lack of aural awareness in those around me, a challenge I continue to face daily. As I developed my ear over time, first as a guitarist and later as a composer and sonologist, I started appreciating the soundscapes and sonic scenes around me just as much as I did visual imagery, in all the places I visited, but also in my own everyday environment. When I began working with electroacoustic music, I was captivated by the idea of being able to capture sounds from specific places, times and situations that had a special significance in my life, such as the sounds made by objects in my workplace, or in the different places where I lived. Transforming those sounds and turning them into compositions seemed to me a very powerful way to capture a moment in time and turn it into something meaningful that would always stay with me. I saw this process as a kind of augmented sonic snapshot that captured some of the essence of those moments, but without simply reproducing recorded sounds. What appealed to me was not concerned with reproducing what was heard exactly, but rather with capturing some of the feelings that those specific sounds evoked in me. I am particularly fond of the music of Bernard Parmegiani, and am well acquainted with the long tradition of musique concrète, as well as with music based on field recordings. But in my own creative work I have always felt more drawn to synthetic, instrumental, or highly-processed recorded sounds, and I would usually only use real world sounds as a starting point. However, these sounds would usually be so heavily processed that they would lose all discernible connection with their original source. I was also more drawn to specific sound objects, rather than to complete natural soundscapes, the way that a hypothetical painter could be captivated by a particular color present in the landscape, which could then be used in a painting of a different, imaginary landscape.

After living completely alone for the last decade, I became quite accustomed to silence. Often the only direct sounds I would encounter daily in my environment were those produced by my own actions, as there were no voices or activities from others around me, other than occasional annoying sounds from my neighbors that I could hear through the walls. This became even more noticeable during the isolation periods of the pandemic in 2020, and as everybody started talking about and reflecting on a kind of isolation, and the silence that came with it, that I was rather used to already, I also started reflecting on this situation and on the impact that the sounds of our daily personal environment can have on us and on our feeling of connection with other people and places. These sounds can also affect our memory of the past and help us form new memories that we will carry into the future. As a result, I began recording some of the sounds in my environment that were most prominent in my day to day life at the time, those sounds that really captured my curiosity when I encountered them and that seemed like interesting sound colors to paint with. Soon after, I decided to take some of those sounds and compose a piece with them, using this also as a challenge and a departure from my usual methods of composing electroacoustic music with mostly synthetic or highly-processed sounds, and trying instead to preserve more of the essence of those sounds that I experienced every day and that had become my companions during that time.

This piece is therefore different from most of the other works in my portfolio, as it makes use of real world sounds in a much more prominent and recognizable way, and employs very few purely synthetic sounds. The recorded sound material comes from the following sources:

1- The door in my home studio, especially the squeaking sound that it made when opening and closing.
2- The oven in my kitchen, striking its metal frame from the inside and rattling its metal grid with a spoon.
3- A dish rack in my kitchen being dragged on the counter, rattled with a spoon, and excited with a violin bow.

The recorded sounds appear processed through filtering and dense networks of delay lines, convolved with synthetic sounds, or resynthesized with changes to their spectra, but they maintain some clear timbral elements of the original sources. The quality of the recorded sounds is not pristine but rather somewhat noisy, as a result of the home environment where they were recorded. But this is something that I embraced, rather than being bothered by it.

This work is also different from others in my portfolio in its approach to spatialization. Even though the piece was also realized in Ambisonics, most of the sounds are placed in front of the listener, rather than all around them. The spatial placement of the individual sounds was determined by the stereo processing when transforming the samples, for example by panning each tap of a delay line to a different point in the stereo field.[13]

As the piece develops, different elements are introduced at specific times coming from other directions, and some sounds are granulated and projected all around the listener, but for the most part there is very little movement of individual sounds within the surround sound field. The piece also moves at a slower pace than most of my other works, with more time to breathe and bigger contrast between sections.

The piece starts with metallic percussive sounds coming from the oven grid samples, and singing-like sounds generated from the squeaking door are introduced shortly after, with the two layers building up simultaneously. The first section ends with a clear percussive strike similar to the opening, and as these sounds suddenly stop completely, an atmosphere of harmonic sounds starts to play, creating a very different atmosphere. In contrast to the previous section, these sounds are not static in space, but slowly move around the listener like clouds of memories, as if we were suddenly transported elsewhere by becoming lost in our thoughts and recollections of other places and times. The source of this material is also different in origin, coming from resynthesized and transformed recordings of Russian Orthodox vocal music I was listening to at the time. These sounds were of course not part of my everyday physical environment, but they are related to the sounds that I would experience when listening to music throughout the day, or in my memory when remembering the many concerts that I would normally attend at other times in my life and that were suddenly not

[13] On a technical side note, starting with this piece I made a switch from 3rd to 7th order Ambisonics for my fixed media works, using 64-channel tracks in my sessions. Even though the difference would not be perceivable in my own studio, where I mixed with headphones or on a quad setup, I decided that rendering and archiving the masters in 7th order was a good way to preserve my work with the highest possible spatial accuracy for performances in suitable venues such as BEAST, and for any kind of downmixing to be done in the future, so I adopted this as my standard moving forward.

accessible anymore during that period. Metaphorically, this section feels like an escape from the everyday sonic environment, mostly through memory and imagination.

The original percussive sound material starts coming back in the next section, and gradually builds up again, as if we were suddenly pulled back into the real world around us and its sounds, along with the feelings of anxiety and disconnection that one could sometimes experience during the isolation of that period. Towards the end of the piece some synthetic sounds are added, along with other metallic rattling sounds. The spatial elements also become more dispersed and hectic at this point, while the low voices and sustained sounds from the squeaking door material remain present and eventually fade away, with a short high metallic sound gesture punctuating the conclusion of the piece.

The title makes reference to the feeling of being lost in time and space, connected through memory to other places and times, but in reality far away from them, and at once digitally connected to the whole world, but also completely physically isolated and with no real contact with people, thus close to the whole world, but at the same time situated nowhere at all.

Working on this piece was a much more intuitive process compared to the previous ones in the portfolio, and I found this very enjoyable and satisfying. It was also a good reminder of the power of real world sounds and how useful they can be for specific musical purposes, which is something that I will keep in my repertoire of tools along with the synthesis techniques that I explored in other pieces. I was also happy to, in some sense, get away from my own typical electronic sounds and habits and try different ways of doing things, while still staying true to my own aesthetics and personal style. Over time I have found this piece to be rather peaceful and enjoyable to listen to compared to some of my other more sonically aggressive works.

5. INTERLUDE

Fixed media acousmatic work
Year of composition: 2022
Duration: 9:57
Format: 7^{th} order Ambisonics

Overview

This is an acousmatic work composed with noise textures generated by chaotic systems, along with sampled sounds from various household objects. These sounds are processed using delays, resonators, and spectral techniques to create slowly evolving textures and pulsating micro-rhythms.

Compositional Ideas and Process

This piece was originally conceived as part of a series of acousmatic works, many of which are included in this portfolio and feature dense sound masses and noise textures. In contrast, this piece offers a much quieter and more static listening experience, serving as a perceptual break from the more intense noise pieces. It presents a quiet interlude that very gradually builds to moments of thick noise before quickly dissolving again. This is where the title of the work comes from. The piece felt like a pause compared to most of my other works from that period, as it features slowly-moving material that is much less dense and aggressive, especially during the first part. I also imagined this piece as existing in between the previous piece, *Nowhere,* and other complementing work based on similar material, or as a piece that would go in between more active pieces in a concert or album. It is also related to *Nowhere* in that it uses some of the same source material from household objects, but aside from the opening and closing gestures, the original sources of the sounds here are completely unrecognizable. The synthetic material also originates from the same chaotic sources used in other pieces, but it is processed in a distinctly different way here, resulting in a completely different sonic outcome. This piece asks for a different kind of listening compared to other works in my portfolio, requiring a more relaxed state of mind where one can focus on the small details and the micro-fluctuations of the sonic material, rather than being overwhelmed by piercing sounds and walls of noisy textures.

The piece begins with a percussive gesture: an unprocessed sample of a metal oven grid being struck with a spoon, similar to the previous piece. This sound connects the two works together and also frames the beginning and end of this piece, reappearing towards the very end. Other recorded sounds appear sporadically throughout the piece, but only heavily processed and combined with other textures. As the initial percussive gesture fades away, a noisy but quiet and slowly-moving sound is introduced, and remains present throughout most of the piece. This was produced using synthetic material from chaotic generators, either controlling oscillators or recording their direct output as sound. The material was then processed through banks of bandpass and notch filters, leaving out most of the original spectrum and revealing only thin layers of crackling noise and artifacts. As layers of these sounds interact with each other, they result in thin noisy textures with ringing and pulsating elements, presenting small fluctuations that happen as the source material changes, and as the parameters of the filtering network are modified over time.

At around the 2:45 mark, we hear a gesture resembling a scream that stands out from the rest of the material. This sound originates from one of the chaotic generators, when its parameters were adjusted and it settled into a steady state around an attractor. This high sound is followed by other similarly pitched clusters that hint at material appearing in the second half of the piece. However, these sounds are fleeting, quickly vanishing and leaving us again with the quiet, noisy textures and their slow movement.

The overall density of the combined material gradually changes over time as the different voices interact with each other and pile up, and they are positioned at different points in the virtual sound field, often moving slowly in space. Equalization and additional filtering were also used to bring out some frequency components in the material and to create separation in the different layers, as well as to add subtle movement.

Six minutes into the piece, a new sound gradually emerges, starting in the low register and later appearing higher up as well. This material is similar in origin to what was used earlier, but it is reproduced at a higher amplitude before being fed to the filtering network, and the parameters are set in such a way that it results in bell-like clusters of sound. These clusters build up throughout this section, consisting of the last third of the piece, and they almost obscure the quieter, noisier sounds that remain in the background, creating the impression towards the end of the buildup of multiple large church bells ringing simultaneously. The piece reaches its climax at around 9 minutes, and after a final loud noisy gesture all the clusters suddenly fade away and we hear a percussive metallic sound similar to the opening. As this sound fades away, the quiet sounds from the beginning remerge into the foreground like they did at the beginning, but now instead of continuing and building up, they wind down as well, and the piece ends when this quiet texture fades into silence.

I view this piece as a kind of sound meditation, where we begin lost in introspection, and then internal forces build into a storm that erupts and quickly dissipates, leaving us awake again. I aimed to explore a different mode of listening and pacing, and I was satisfied with the result of this work, as it complements some of my other pieces while revealing a different side of my creative approach and an alternative way of exploring source material from similar origins.

6. IN THE FOG

Fixed media acousmatic work
Year of composition: 2023
Duration: 10:58
Format: 7th order Ambisonics

Overview

This work is composed of material produced using chaotic generators, which is then fed through a signal processing patch consisting of inter-modulated devices with audio and control signal feedback. This process results in slowly changing sounds with ringing high frequencies and a dense spectrum. Multiple versions of these sounds are layered and arranged in space, resulting in static atmospheres that develop gradually and produce different micro-rhythms and interference patterns. The title is related to the sonic metaphor of being surrounded by a dense cloud of slowly moving fog.

Compositional Ideas and Process

I started producing the materials for this piece very spontaneously, by simply taking some of the sound files I had previously generated for other pieces using chaotic generators, and putting them through a patch I made that consisted of interconnected processing devices in an audio and control signal feedback network. In this sense, the chaotic generators were used as an agnostic noise generating device, and the results were treated as a recorded sample or found sound object. The real character of the sound was developed by tweaking the processing chain and further manipulating the results through creative filtering, as well as by overlapping multiple copies of the sounds with small pitch fluctuations achieved through the processing, or in some cases through careful manipulation of the playback speed of the sound files. The noisy nature of the initial material and its inherent micro-rhythmic fluctuations were crucial elements, as this introduced intriguing variations and led to emergent properties during the processing stage. These characteristics helped guide the direction of some of the musical transformations that were later chosen.

The samples were processed several times in parallel through the same patch. Because of the feedback elements of the processing network, which produced constantly changing behavior, the resulting sounds were very similar in their overall shape and spectral content, but had many small fluctuations and different pitch and micro-rhythmic elements. Several copies of these processed sounds were then layered and arranged in 3D space to produce a slowly changing mass of sound surrounding the listener. This creates the feeling of being surrounded by a fog of sound, and it is particularly effective when listening to the piece in an immersive environment.

Once the piece started taking shape, I began thinking of it as a sort of orchestral piece made with electronic sounds. Most of my electroacoustic pieces tend to have a somewhat monolithic structure, with slowly changing high density textures and very few pauses or moments of silence. One of the main challenges that I often encounter is how to control the density of the material, particularly as the spectrum becomes saturated with multiple noise-rich sound elements. For this piece, I decided to think of the arrangement of the sound layers in a way similar to what I would do if I were writing for an orchestra, as I have done in the past. This mindset was invaluable, allowing me to, in a sense, orchestrate the material to create the soundscape I envisioned. It provided a practical approach to mixing and arranging material in electroacoustic music, a technique that has stayed with me and has continued to influence my practice beyond this piece.

It is often said that computers can generate any sound one can imagine. I have always found this to be a somewhat misleading way to think about computer music. In principle, the computer can produce any sound, but this is only useful if we know *how* to produce those sounds through our available means and techniques, whether they be code, virtual modular synthesizers, plugins in a DAW, or any combination of software and hardware tools. In practice, we often end up working not with the sounds we imagine, but rather with the sounds we discover as we're trying to realize the sounds we imagine, or as we simply explore the tools at our disposal. In some extreme cases, the process of imagination is even turned upside down, and composers focus on the results they obtain through different planned procedures or experiments – or as Agostino Di Scipio would put it, as the result of *desirable interactions* that the composer designs (Di Scipio, 2003). Composers can then try to shape these resulting materials into structures that are musically interesting, or in some extreme cases, as suggested by Herbert Brün (Brün, 1970), they can even try to learn to like what they hear, rather than to hear what they like or what might have been originally imagined, or just let the sounds be themselves, as John Cage would put it (Cage, 1961). This approach can in any case be useful at least for discovering new sounds and paths that perhaps we wouldn't be able to imagine given our limitations and previous experience.

In my own practice, the balance between imagination and discovery is something that I have always found interesting, and I think that most of the time I tend to find the space in between the two extremes to be the most fruitful. Sometimes I start working with the materials I generate, and then try to develop them based on what I find appealing as I work with them. But one can easily lose track of the goal and the overall form as well, if we do not pay attention to the results and how they fit together. In this sense, in my own development as a composer I have tried to investigate interesting methods and tools for generating sound, such as the use of non-linear dynamical systems that I have discussed earlier, but also to develop my ability to realize the musical experiences that I imagine or that I would like to experience.

In the process of writing this piece I tried to focus on the different elements of arranging dense layers of material and controlling the perceived result – in some sense, the orchestrating of the music, to use an analogy from instrumental music – through the use of audio production and mastering techniques such as filtering and equalization, as well as careful spatial placement of the different layers of material. I see this as part of the process of learning to use the computer to actually produce the sounds I imagine and want to create.

Other elements were incorporated in order to balance the palette of sounds in the piece, though most of them were produced using the original feedback processing network. This includes the low sounds and clusters that we hear in the piece. There are also simple sine tones throughout the work, usually in close proximity and producing beating patterns, that are added in order to emphasize certain parts of the spectrum, and to interfere with other elements in the sound masses.

Towards the end of the piece there are some prominent comb filtered sounds and brief granular gestures that were added to give momentum to the piece in those sections.

The manipulation of playback speed of identical samples was also used to produce further interference and beating patterns. I found this technique to be very effective alongside the other elements of the piece, and it helped to achieve a sense of space when these copies are placed at different points around the listener, or even close together in the stereo field.

The piece opens with a texture of sustained sounds that are spread out in space and slowly beating as they go through slight fluctuations in their pitch and amplitude. This produces interesting micro-rhythms and high-ringing sounds. A bass sound is later introduced expanding the spectrum, and as these voices interact we get an effect that might resemble an orchestra playing sustained notes. The density changes as some of the bass sounds drop out, but the ringing textures continue, with new pitch fluctuations and beating patterns, and a very slow development of the material. Towards the middle of the piece we get a new cluster in the mid-register that takes over the foreground, and other beating voices start joining in, along with a low pulsating sound resembling a bass drum playing tremolo rolls. These textures continue to build, culminating in a brief crescendo that erupts into an explosive gesture — a granular cloud that falls like sparkling rain. This moment transitions into another set of sustained cluster sounds and gently shifting lines. Another high cloud, with a more gentle timbre, appears later on, produced from granulation of the sustained material and spread out in space around the listener. Additional voices join in, including filtered broad-spectrum noise and synthetic clouds, building up to a mini climax. Meanwhile, other sustained voices begin a descending glissando that transitions into brief bell-like ringing textures. As the main voices fade away, we are left with subtle high ringing sounds and a texture of quiet bubbly noise. At the very end we hear only a pulsating low sound that slowly vanishes as the piece ends, as if the sonic fog was finally dissipating.

I worked on this piece during a particularly emotionally challenging period of my life, as I dealt with profound feelings of loss and despair. I was able to immerse myself in this fog of sound and find some calm there, as I tried to fine-tune all the minute details of the piece. At the same time, many of the sonic element I was trying to control seemed to constantly remain out of my reach, just like real fog. They simply kept floating away from me and taking their own shape, reminding me of how we can only control the things and circumstances around us to a very limited extent and we simply have to learn to live with many things we cannot change.

7. WARPED DREAMS

Fixed media acousmatic work
Year of composition: 2023
Duration: 6:02
Format: 7th order Ambisonics

Overview

This is a fixed media acousmatic work produced in 7th order Ambisonics. The main source material comes from heavily processed samples of instrumental recordings that are blended with synthetic sounds and juxtaposed in thick layers. Spatialization and gestural movement play an important role, especially toward the end of the piece.

Compositional Ideas and Process

Running at just over six minutes, this is the shortest and most condensed piece in my portfolio outside of the Chaos Studies. Its form is rather simple, with two main sections, building up density in multiple layers and then, after a short pause, moving towards a short contrasting climax of whooshing gestures and then quickly fading away.

The idea for this work came from the experience of attending a computer music conference online, where I occasionally found myself accidentally listening to multiple pieces simultaneously as I tried to catch up with the program. For instance, I might be listening to a recording of an earlier concert while I was waiting for a live stream, which would then suddenly begin playing without me being aware of it. It sometimes took me a moment to realize that two pieces were playing simultaneously, and I became intrigued and fascinated by the unexpected combinations of sounds I encountered, only to discover an instant later, much to my disappointment, that the sounds were coming from two completely different sources, neither of which seemed nearly as interesting when heard on its own. Listening to multiple sound streams simultaneously like that can sometimes feel overwhelming and disorienting. However, after experiencing this a few times—initially by accident, but later deliberately—I began to appreciate the complexity of listening to multiple streams at once, and enjoying the process of discovering the intriguing combinations of timbres and rhythms that emerged by chance, as well as the lingering sensation of sensory overload that stayed with me at the end of the day, even affecting my sleep afterwards and the content of my dreams.

This experience also reminded me of some of the aleatoric pieces of John Cage in the 1950's, the music of Charles Ives with his sonic collages – where he juxtaposes multiple independent lines of music playing simultaneously, in works such as *Putnam's Camp*, from *Three Places in New England* – and some of the electroacoustic music of Iannis Xenakis such as *Bohor*, where multiple lines of independent material pile up into thick masses of sound. My piece differs significantly from those works in style, form, and length, but it shares the concept of multiple unrelated sonic lines occurring simultaneously to create something entirely new, distinct from the original components. This juxtaposition profoundly influences our perception of each of the individual layers, creating a complex musical experience as a result.

I was also interested in recreating the sensation of cumulative sensory overload that builds up over time after a long day of traveling or attending multiple concerts at a festival, or the feeling we experience when playing several media streams simultaneously at home, for example when launching a browser session that had multiple tabs of music videos open and they all start playing at once, or when listening to audio demos on a website where launching one clip doesn't automatically stop the others. This kind of overload can also occur when trying to listen to something on a phone while on a train or in a crowded place. At the end of the day, we process the recollections of those sounds and experiences in our memory and dreams, where they sometimes reappear strangely distorted and in unexpected combinations, as if warped in time and space. This is the inspiration behind the title of the work. The piece serves as a reminder that the sensory saturation we often experience in modern life can also be a source of beauty and enjoyment – if we just learn to listen to it in the right way. Much like the cocktail party effect, our perceptual choices continually shape how we experience the sonic landscapes around us, making active listening a form of composition in itself. I believe this is something that we experience to some extent every day and that is worth exploring and cultivating, as it can be treated as a form of aural day dreaming or hallucinating when done intentionally, and create intriguing musical experiences, as well as inspiration for music creation. This work is inspired by these ideas, and can be seen both as a recreation of that process of active listening and aural hallucination, as well as an act of presenting complex material that can serve as the starting point for such an experience of active and selective listening, in the context of a deliberate musical experience.

The piece opens with a quiet synthetic bass sound, and just a moment later a thunder-like cloud appears, immediately followed by clouds of high metallic sounds. The low clouds were created by granulating and filtering recordings of percussion instruments, and they remain a constant element throughout the first part of the piece, occasionally receding into the background. The high metallic sounds come from processed recordings of flute, female voice and violin. These appear in multiple copies and with different degrees of spectral processing, pitch shifting, and time stretching, and are present in some form or another throughout the entire piece. Synthetic sounds made from small clusters of sustained high notes are also mixed in with this material. The sounds are spread out in space, appearing mainly at the front, but with some grains scattered all around the listening field. There is a third important element in the first section, consisting of processed electromagnetic recordings with a heavy bass content. These are also processed with granulation and filtering, and remain constantly in the background. The multiple layers of sound form a dense atmosphere that develops slowly over time, with different voices coming to the foreground of the overall texture only for brief moments.

Structurally, the second part of the piece begins around the 4-minute mark, when the percussive clouds abruptly stop and the other voices fade away momentarily, revealing synthetic clusters in the mid-register for a brief pause in activity. This leads into a climax that introduces very different material, with stuttering sounds and whooshes moving throughout the sound field in quick gestures. Granulated samples of metallic sounds and impacts were used for this material, mixed with synthetic electronic sounds. Some of the previous voices come back momentarily and then start dying away as the fast gestures disappear. A slow-moving low register sound is revealed at the end, and the piece ends with this sound ringing out and fading away, leaving us in a silence loaded with the lingering echoes of the dense sonic streams we just heard.

8. BROKEN HOURGLASS

Fixed media acousmatic work
Year of composition: 2024
Duration: 08:53
Format: 7th order Ambisonics

Overview

This is a fixed media electroacoustic work produced in 7th order Ambisonics. It uses raw electromagnetic recordings, heavily filtered acoustic sounds, and glitchy synthetic sounds produced with chaotic generators.

Compositional Ideas and Process

The starting point for this piece was a series of noisy instrumental recordings that were put through modulated banks of filters around narrow frequency bands. This process stripped away most of the original sound spectrum, revealing only thin slices that change over time, while retaining many of the original amplitude contours. Artifacts from the modulation process also heavily colored the material. This technique was used to generate the main voices that run throughout the first part of the piece. The resonating frequencies of the filters produce noisy textures that constantly change as the multiple bands are mixed and interact with each other.

A second element is introduced 16 seconds into the piece: this is a texture that, in spite of coming from a completely different source, blends well with the other voices, becoming a sort of background at first, but eventually moving to the foreground and partially taking over. The source of this sound is a recording of electromagnetic waves, captured during a train ride between Rotterdam and The Hague, in the Netherlands, with a Soma Ether device. Multiple voices of similar material are gradually added and eventually become the dominating sonic element as the piece develops, with the electromagnetic sounds becoming denser as the train approached a station in the original recordings, resulting in stronger magnetic fields being captured by the electromagnetic recording device.

Shortly after the 1 minute mark, a third element is added, consisting of short noise bursts and glitches. These sounds were produced using a patch that models a chaotic analog circuit using oscillators and clock dividers, connected to a Hopalong Map module. The two are cross-modulated in a complex control signal processing path, resulting in short and unstable bursts that only rarely settle into stable low tones for brief moments. These sounds are spread out in space, creating contrast and punctuating the noisy textures of the filtered voices, in a sort of spatial and timbral counterpoint.

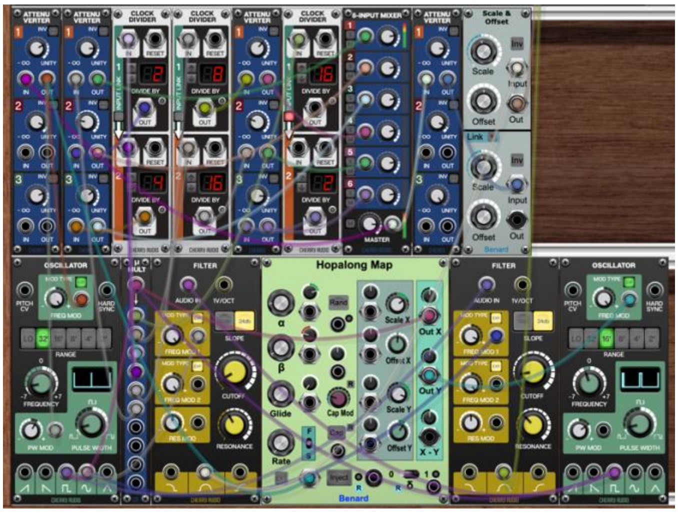


Fig. 16 – The patch used to produce the noise bursts

New voices are introduced three minutes into the piece, consisting of synthesized harmonic material that is also being filtered, but with very slow modulation of the filters and gradual changes in pitch. These voices are layered into the mix as the original lines become more active, with the source material speeding up and the modulation rate increasing, resulting in more pronounced changes in the amplitude contours and producing accelerating gestures. At the same time, the sounds start moving more quickly within the virtual sound field, reinforcing the perceived increase in pace.

The density of the material gradually increases, and a rhythmic gesture is added, produced through the use of pitch shifting, stuttering, and rhythmic envelopes to process some of the harmonic material and creating voice separation. Shortly after this happens, the original filtered voices drop out completely, and other voices with a rich spectrum take their place, while the noisy background continues.

As the electromagnetic recordings move toward their climax, the density of the other voices increases as well, following this contour. This effect is accentuated by adding multiple processed copies derived from the original voices, along with high granulated sounds. This buildup suddenly leads to a deep, low sound, followed by multiple voices echoing elements of the electromagnetic sounds at different pitches, dispersed in space to create a cluster. The cluster then dissolves into a descending granular texture that quickly fades away, revealing the underlying noisy texture that has been present throughout and bringing it to the forefront.

The piece ends with a small coda where harmonic material makes a reappearance, along with some of the short glitchy sounds from earlier, then fading into a single pulsating tone for a brief moment that is then extinguished by a final gesture consisting of a burst of noise.

Although the sound materials for this piece originate from diverse sources and were chosen without a systematic categorization, they fit together and complement each other timbrally, and were selected intuitively as the piece evolved, much like adding colors to an abstract painting from a palette of recently generated and collected sounds. These sounds also share a common element: they reveal something often present but unheard, whether through slices of the spectrum unveiled by filter banks, electromagnetic recordings, or glitches that emerge from interpreting chaotic systems as raw audio.

The title was chosen after the piece was completed, inspired by the idea of our perception of time becoming distorted in certain mental states and life circumstances. Sometimes, months can pass in what feels like the blink of an eye, as if the sands of time were leaking through a crack in a broken hourglass. The glitchy sounds and granular textures evoke the sensation of sand surrounding the listener, while the sustained tones and rhythmic gestures can be imagined as a malfunctioning clock. The electromagnetic recordings add another layer of meaning, revealing aspects of the environment that we usually overlook but that constantly move to their own rhythm all around us.

FUTURE WORK AND CLOSING THOUGHTS

Developing my collection of modules has given me valuable insight into what it takes to release and maintain commercial software. While I am still interested in pursuing this path, I now have a clearer understanding of the challenges involved. Moving forward, I will carefully consider how much time I can realistically devote to software development, perhaps implementing some of my ideas slowly, but ensuring it doesn't take too much time away from my composing. It remains clear to me that music creation must remain my primary focus, as that is where my true passion lies.

In my future research, I plan to explore several areas of interest related to non-linear dynamical systems. One key focus will be the use of chaotic generators to create complex time and rhythmic structures by generating time intervals, which could also affect the clocking of the generators themselves in feedback loops. I am also intrigued by the potential of conducting signal processing within a chaotic generator — outputting a signal for processing, then reintegrating it to calculate the system's next step. Another area of interest involves coupling chaotic module outputs to systems of resonators and other stabilizing or filtering mechanisms, and the use of concatenative synthesis techniques to combine the different outputs of single or multiple chaotic systems.

I intend to investigate different generators for granular synthesis more thoroughly and design systems for live performance. This includes exploring coupled generators in complex feedback loops and incorporating elements of human and room-dependent signal processing. These aspects will form the foundation of my upcoming work with non-linear dynamical systems.

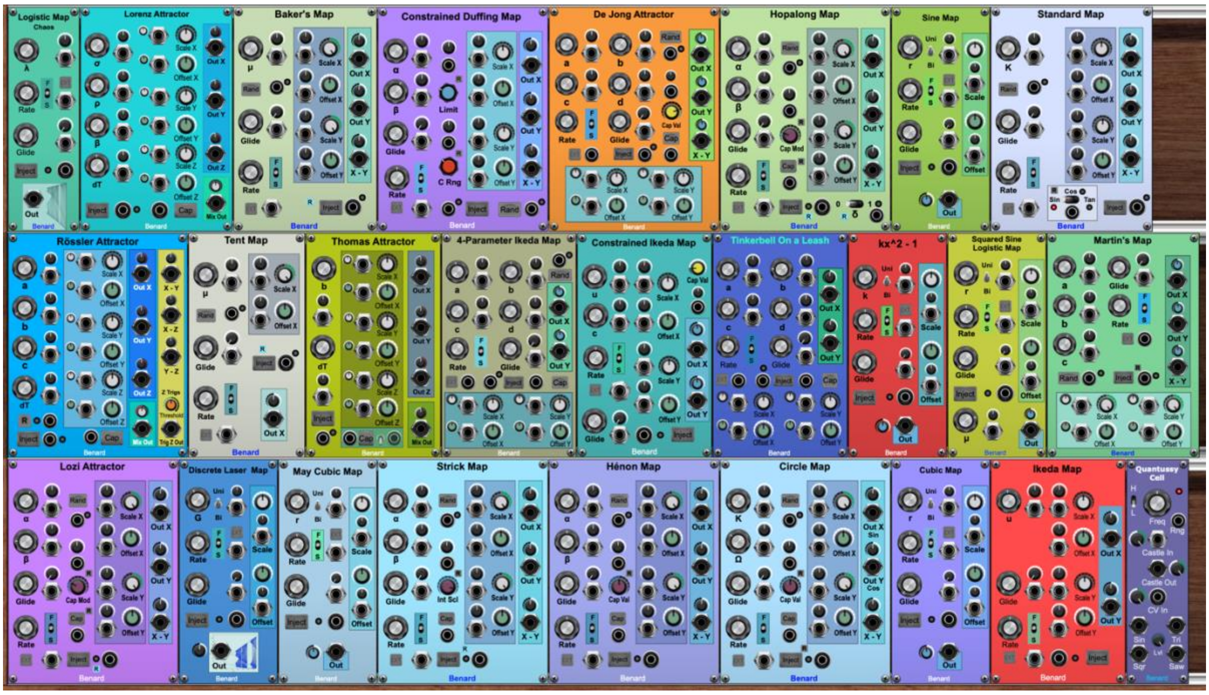
Additionally, I am eager to explore cellular automata and other systems with simple rules that produce complex behavior. I hope to experiment with their potential for both sound synthesis and rhythmic structure generation, and I may even implement some of these systems as modules.

From a compositional point of view, working on the pieces in this portfolio allowed me to refine my techniques for music production, especially in the context of dealing with noise and dense sonic masses, and with immersive audio in Ambisonics. As I found myself reworking some elements of the pieces over and over, I embraced the idea of recursion and emergent properties, as encountered in the chaotic systems I was working with, as a metaphor for the compositional process. I thought of the process of assembling, reorganizing, and reworking musical material on successive runs, and refining the results on each pass, as the works gradually take their final shape and the desired music slowly emerges. This served me as a useful analogy and inspiration for composing, which I will take with me moving forward.

APPENDIX A

Benard Chaos Modules in Voltage Modular

- Aizawa Attractor
- Baker Map
- Chen Attractor
- Chua Circuit
- Circle Map
- Constrained Duffing Map
- Cubic Logistic Map
- De Jong Attractor
- Duffing Map
- Gauss Map
- Gingerbread man Map
- Gingerbread man Map Variation
- Hénon Map
- Hopalong Map
- Ikeda Map
- Kx^2 - 1
- Laser Map
- Lozi Attractor
- Lorenz Attractor
- Logistic Map
- Martin’s Map
- Quadratic Map
- Rössler Attractor
- Sine Map
- Squared Sine Logistic Map
- Standard Map
- Strick Map
- Thomas Attractor



Benard Chaos Modules in Voltage Modular

APPENDIX B

Chaos Software and Eurorack Modules

Links below were accessed on August 26th 2024.

- Benard Modules
https://store.cherryaudio.com/manufacturers/benard

- Voltage Modular
https://cherryaudio.com/products/voltage-modular

- Dawsome Kult
https://www.tracktion.com/products/kult

- Dudas and Sier Max Chaos Library
https://s373.net/code/A-Chaos-Lib/A-Chaos.html

- Eventide Generate and Pendulate
https://www.eventideaudio.com/plug-ins/generate/
https://www.eventideaudio.com/plug-ins/pendulate/

- Falcon
https://www.uvi.net/falcon

- Hetrik
https://library.vcvrack.com/HetrickCV

- Ian Fritz
http://ijfritz.byethost4.com/Chaos/ch_over.htm

- Kyma
https://kyma.symbolicsound.com/

- Max
https://cycling74.com/products/max

- Modular Grid
https://modulargrid.net/

- Nonlinear Circuits
https://www.nonlinearcircuits.com/modules

- Snazzy FX
http://snazzyfx.com/

- SuperCollider
https://supercollider.github.io/

- Vital
https://vital.audio/

- Xfer Records Serum
https://xferrecords.com/products/serum/

APPENDIX C

Musical References

Links to versions of the music available online are included under each entry. These were accessed on August 26th, 2024.

Dunn, David. (2007). *Autonomous and Dynamical Systems*. Edition RZ (ed.RZ 1016).
Lorenz can be accessed online at: https://www.youtube.com/watch?v=hdx2oihp7IE
Nine Strange Attractors at: https://www.youtube.com/watch?v=aTdIYxVR5lc

Ives, Charles. (1994). *Three Places in New England: Putnam's Camp, Redding, Connecticut*. Conducted by Michael Tilson Thomas, performed by the Boston Symphony Orchestra. Sony Classical, CD.
https://www.youtube.com/watch?v=Jcsi56_VStY

Satriani, Joe. (1998). *Searching*. On *Crystal Planet* [CD]. Epic Records.
https://www.youtube.com/watch?v=EEMdyqncToA

The Smashing Pumpkins. (1995). *Bullet with Butterfly Wings*. Performed by The Smashing Pumpkins. *Mellon Collie and the Infinite Sadness* (CD). Virgin Records.
https://www.youtube.com/watch?v=8-r-V0uK4u0

Truax, Barry. (1986). *Riverrun*. Digital Soundscapes (CD). Cambridge Street Records.
https://www.youtube.com/watch?v=u81IGEFt7dM

Truax, Barry. (1987). *Wings of Nike.* Digital Soundscapes (CD). Cambridge Street Records.
https://www.youtube.com/watch?v=e5EhCdqqvsY

Xenakis, Iannis. (1990). *Bohor*. *Electronic Music* (CD). Mode Records.
https://www.youtube.com/watch?v=t_f-R-mNuLE

Xenakis, Iannis. (1995). *GENDY3* [CD]**.** Mode Records.
https://www.youtube.com/watch?v=5qS5lqbx9H0

Xenakis, Iannis. (1995). *La Légende d'Eer* [CD]. Mode Records.
https://www.youtube.com/watch?v=HyDL2aokdek

Xenakis, Iannis. (1995). *S.709* [CD]. Mode Records.
https://www.youtube.com/watch?v=Zmi2EVb7kQU

BIBLIOGRAPHY

• Berdahl, Edgar, and Viator, Landon. (2021). "Sound Synthesis by Connecting a Chaotic Map to a Bank of Resonators." *Proceedings of the International Computer Music Conference (ICMC).*

• Bidlack, Rick Aaron. (1990). *Music from Chaos: Nonlinear Dynamical Systems as Generators of Musical Materials.* Doctoral dissertation, UC San Diego.

• Bidlack, Rick Aaron. (1992a). "Music from Chaos: Nonlinear Dynamical Systems as Generators of Musical Materials." *Perspectives of New Music*, 30(1), 38–48.

• Bidlack, Rick. (1992b). "Chaotic Systems as Simple (But Complex) Compositional Algorithms." *Computer Music Journal*, 16(3), 33–47.

• Bravo Benard, Hector. (2006). *The Influence of Thought and Technology in Music.* Master's thesis, Institute of Sonology.

• Cage, John. (1961). *Silence: Lectures and Writings.* Wesleyan University Press.

• Collins, Nick. (2011). "Implementing Stochastic Synthesis for SuperCollider and iPhone." *Proceedings of the Xenakis International Symposium*.

• Damiani, F., Manzolli, J., and Tatsch, P. J. (1999). "A Non-Linear Algorithm for the Design and Production of Digitally Synthesized Sounds." *ICMP'99 Proceedings*, Campinas, Brazil.

• DeFilippo, David Morrison. (2023). "Coupled Oscillator Systems." *Doctoral Dissertation*, University of California San Diego.

• Di Scipio, Agostino. (1990). "Composition by Exploration of Non-Linear Dynamic Systems." *Proceedings of the 1990 International Computer Music Conference.*

• Di Scipio, Agostino, and Prignano, Ivana. (1996). "Synthesis by Functional Iterations: A Revitalization of Nonstandard Synthesis." *Journal of New Music Research*, 25(1), 31–50.

• Di Scipio, Agostino. (1999a). "Synthesis of Environmental Sound Textures by Iterated Nonlinear Functions." *Proceedings of the 2nd COST G-6 Workshop on Digital Audio Effects (DAFx99)*, Trondheim, Norway.

• Di Scipio, Agostino. (1999b). "Chaos and the Emergent Digital Aesthetic." *Leonardo Music Journal*, 9, 5-10.

• Di Scipio, Agostino. (2001). "Iterated Nonlinear Functions as a Sound-Generating Engine." *Leonardo*, 34(3), 249–254.

• Di Scipio, Agostino. (2003). "Sound is the Interface: From Interactive to Ecosystemic Signal Processing." *Organized Sound*, 8(3), 269-277.

• Dobereiner, Luc. (2011). "CompScheme: A Language for Composition and Stochastic Synthesis." *Proceedings of the International Computer Music Conference (ICMC)*.

• Dodge, Charles, and Thomas A. Jerse. (1997). *Computer Music: Synthesis, Composition, and Performance.* 2nd ed. New York: Schirmer Books.

• Dunn, David. (1997-1998). "A Chaos of Signs: Making Noise into Music." *The Exploratorium Magazine Online* (Winter).

• Galeano, Eduardo. (1993). *Ventana sobre la utopía.* In *Las Palabras Andantes*. Siglo XXI Editores.

• Gleick, James. (1987). *Chaos: Making a New Science.* New York: Viking.

• Harley, James. (1994). "Algorithms Adapted from Chaos Theory: Compositional Consideration." *Proceedings of the International Computer Music Conference (ICMC)*, pp. 54–57.

• Harley, James. (1994). "Generative Processes in Algorithmic Composition: Chaos and Music." *Leonardo Music Journal*, 4.

• Hoffmann, Peter. (1996). "Implementing the Dynamic Stochastic Synthesis." *Journées d'Informatique Musicale*, Île de Tatihou, France.

• Hoffmann, Peter. (2003). "Music Out of Nothing? The Dynamic Stochastic Synthesis: A Rigorous Approach to Algorithmic Composition by Iannis Xenakis." Doctoral Dissertation, Technische Universität Berlin.

• James, Jamie. (1993). *The Music of the Spheres: Music, Science, and the Natural Order of the Universe.* Copernicus.

• Khosravi Mardakheh, Milad, & Wilson, Scott. (2022). "A Strata-Based Approach to Discussing Artistic Data Sonification." *Leonardo*, 55(5), 516–520.

• Kundera, Milan. (1999). *The Unbearable Lightness of Being.* Translated by Michael Henry Heim. Faber & Faber.

• Koenig, Gottfried Michael. (1978). "Realization of Musical Compositions by Electronic Means." In *Electronic Music Reports*, Vol. 6, edited by Tomás Marco, 28-52. Utrecht: Institute of Sonology.

• Lem, Nolan, and Orlarey, Yann. (2019). "Kuroscillator: A Max-MSP Object for Sound Synthesis using Coupled-Oscillator Networks." *14th International Symposium on Computer Music Multidisciplinary Research (CMMR)*.

• Lindeman, Eric. (1988). "Routes to Chaos in a Non-Linear Musical Instrument Model." *Proceedings of the Audio Engineering Society Convention.*

• Lorenz, Edward Norton. (1963). "Deterministic Nonperiodic Flow." *Journal of the Atmospheric Sciences*, 20(2), 130-141.

• Lorenz, Edward Norton. (1993). “*The Essence of Chaos”.* University of Washington Press.

• Luque, Sergio. (2009). "The Stochastic Synthesis of Iannis Xenakis." *Leonardo Music Journal*, 19, 77–84.

• Manzolli, J., Damiani, F., and Tatsch, P. J. (1999). "A Non-Linear Algorithm for the Design and Production of Digitally Synthesized Sounds." *ICMP'99 Proceedings*, Campinas, Brazil.

• May, Robert M. (1976). "Simple Mathematical Models with Very Complicated Dynamics." *Nature*, 261(5560), 459-467.

• Mitchell, Melanie. (2009). *Complexity: A Guided Tour.* Oxford University Press.

• Nietzsche, Friedrich. (1995). *Thus Spoke Zarathustra: A Book for All and None.* Translated by Walter Kaufmann. New York: Modern Library.

• Roads, Curtis. (1996). *The Computer Music Tutorial.* Cambridge, MA: MIT Press.

• Rodet, Xavier. (1995). "Basic Models of Musical Instruments as Non-Linear Dynamic Systems: From Harmonic Sounds to Mode Locking." *Proceedings of the International Computer Music Conference (ICMC).*

• Scaletti, Carla. (2018). "Sonification ≠ Music." In A. McLean & R. Dean (Eds.), *The Oxford Handbook of Algorithmic Composition* (pp. 379–408). New York: Oxford University Press.

• Serra, Marie-Hélène. (1993). "Stochastic Composition and Stochastic Timbre: GENDY3 by Iannis Xenakis." *Perspectives of New Music*, 31, 236-257.

• Stewart, Ian. (1989). *Does God Play Dice? The New Mathematics of Chaos.* Oxford: Blackwell.

• Stravinsky, Igor. (1947). *Poetics of Music in the Form of Six Lessons.* Translated by Arthur Knodel and Ingolf Dahl. Cambridge, MA: Harvard University Press.

• Truax, Barry. (1990). "Chaotic Non-Linear Systems and Digital Synthesis: An Exploratory Study." *Proceedings of the International Computer Music Conference.*

• Wishart, Trevor. (1994). *Audible Design: A Plain and Easy Introduction to Practical Sound Composition.* Orpheus the Pantomime Ltd.

• Wishart, Trevor. (1996). *On Sonic Art* (2nd ed.). Routledge.

• Xenakis, Iannis. (1992). *Formalized Music: Thought and Mathematics in Composition.* Revised edition. Stuyvesant, NY: Pendragon Press.

• Zotter, Franz, and Frank, Matthias. (2019). *Ambisonics: A Practical 3D Audio Theory for Recording, Studio Production, and Sound Reinforcement.* Springer.

IMAGE CREDITS

Figure 2: "Rössler-Attractor" by User:Wofl, Wikipedia (https://en.wikipedia.org/wiki/R%C3%B6ssler_attractor#/media/File:Roessler_attractor.png), Licensed under CC BY-SA 2.5.

Figure 4: "Logistic Bifurcation map" by Jordan Pierce, Wikipedia (https://en.wikipedia.org/wiki/Logistic_map#/media/File:Logistic_Bifurcation_map_High_Resolution.png), Licensed under CC0.

Figure 11: "Lorenz System" by Wikimol, Wikipedia (https://en.wikipedia.org/wiki/Lorenz_system#/media/File:Lorenz_system_r28_s10_b2-6666.png), Public Domain.