Sporadic: Mycelial Delay Effect

- Expressivity Through the Lens of Ecology -

Master's Thesis Report

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Abstract:

This project presents Sporadic, a biomimetic audio processor that translates mycelial network dynamics into delay-based audio processing. The system addresses key challenges in biomimetic instrument design: translating ecological processes into musical parameter mappings and balancing autonomous behaviour with user control.
Sporadic implements adaptive network topologies that mirror mycelial behaviour, creating novel delay networks and dynamic feedback systems. User evaluation with eight participants demonstrates successful design, with high ratings for conceptual integrity (6.12/7) and exploration reward (5.62/7).
This work establishes design principles for biomimetic instruments and demonstrates how musical interaction can serve as a pathway for understanding natural systems.

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Abstract:

Dette projekt præsenterer Sporadic, en biomimetisk lydprocessor, der oversætter mycelial netværksdynamik til forsinkelsesbaseret lydbehandling. Systemet adresserer centrale udfordringer inden for design af biomimetiske instrumenter: oversættelse af økologiske processer til musikalske parameterkortlægninger og balancering af autonom adfærd med brugerkontrol.
Sporadic implementerer adaptive netværkstopologier, der afspejler mycelial adfærd og skaber nye forsinkelsesnetværk og dynamiske feedbacksystemer. Brugerevaluering med otte deltagere demonstrerer vellykket design med høje ratings for konceptuel integritet (6,12/7) og udforskningsbelønning (5,62/7).
Dette arbejde etablerer designprincipper for biomimetiske instrumenter og demonstrerer, hvordan musikalsk interaktion kan tjene som en vej til forståelse af naturlige systemer.

Contents

Preface

This work is not a culmination or a grand statement marking the completion of the narrative arc of my education in engineering and sound. Rather, it is an attempt to recontextualise the skills and knowledge gained within the larger frame of a world that fascinates me. This is what emerges from the sponge that soaked in the rain, baked in the sun, and gazed at the stars alongside me. And no, the Danish wordplay on the word "svampe" is not at all lost on me.

It is no coincidence that the natural world sets the scene for this project. It is here countless hours were spent studying the movement of snails and caterpillars, here where the greatest sense of bliss was felt looking down at valleys below, and also here the most visceral frights played out with currents' pull away from shore. Through all these highs and lows, it is in the embrace of nature that time and space have been made manifest most clearly. Here, true connectedness and interdependence is to be found within systems anchored in the present, with histories reaching back as far as the faintest stars in the night sky.

In seeking to translate these natural systems into musical expression, I am not merely borrowing from nature, but acknowledging our place within it. The mycelial networks that inspire this work existed aeons before us and will likely persist long after. Their silent, invisible labour creates the foundation for entire ecosystems, much like the unseen processes that shape the culture emerging from our shared experience of sound and music. This project stands as an invitation to listen more deeply, not just to the resulting sounds, but to the patterns and relationships that make them possible.

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The author extends his sincere gratitude to Dan Overholt, whose invaluable contributions were instrumental (pun intended) to the success of this project. As coordinator, he provided insight and guidance in framing the application of theoretical concepts into a cohesive instrument design. On a personal level, his warmth, enthusiasm and willingness to share his own influences and network of collaborators have made the process of developing, documenting, and evaluating this design all the more rewarding. The knowledge and perspective that he shared will undoubtedly inform my reasoning in the future, be it when thinking of interaction design, thinking about constraints and affordances, and seeking the right sounds in the wrong places.

A huge thanks to my partner for being supportive and always believing in me. And for championing my project even with the n^{th} group of friends we met. Your constant curiosity is a continuous source inspiration to me. Can't wait to see where that takes you and us in the future.

Chapter 1

Introduction

Another Green World

Autumnal Stroll (author's private collection)

At the intersection of ecology, music technology, and design philosophy lies a new frontier for instrument creation, one that draws inspiration not from traditional engineering paradigms but from the complex adaptive systems found in nature. This project explores how biological systems, particularly forest ecosystems and the mycelial networks that form their backbone, can inform the development of dynamic audio processing tools that respond, evolve, and exhibit behaviour reminiscent of living organisms.

"*When the topsoil*
Is kicking up into the storm
And the dust goes dancing
And a billion planets are born"

- Big Thief

The core premise of this work is not to merely simulate or digitally recreate natural processes, but rather to translate the fundamental principles of biological systems into meaningful musical parameters and interactions. By mapping concepts such as nutrient exchange, energy management, and ecological interconnectivity to audio processing parameters, we can create instruments that exhibit organic behaviours: instruments that "breathe," "respond" and "learn" through interaction with musicians.

This project represents both a technical exploration of adaptive audio routing systems and a philosophical inquiry into our relationship with technology and the natural world. By developing instruments that mirror natural systems' responsiveness to environmental conditions, the aim here is to foster modes of musical creation that encourage exploration, wonder, and a renewed sense of connectedness to the world around us.

1.1 Motivation

The motivation for this project arises from several converging interests and observations about modern music technology, ecological awareness, and the creative process.

First, there exists a certain rigidity in much of current digital audio processing. Although digital tools offer precision and reliability, they often lack the organic unpredictability and adaptive qualities that characterise natural systems. Traditional audio effects, such as delays and reverbs, typically operate with fixed parameters that, once set, remain constant regardless of the input material or musical context. This stands in stark contrast to natural acoustic spaces, which respond dynamically to sound sources, constantly shifting and evolving based on input characteristics.

Second, there is growing recognition of the profound ways in which natural systems, particularly forest ecosystems, communicate, share resources, and adapt to changing conditions. The coining of the term "Wood-Wide Web" [1] to refer to the underground mycelial network through which trees exchange nutrients, communication signals, and resources brought these lifeforms back on the front pages of popular science publications. These biological systems demonstrate principles of resource allocation, energy conservation, and network resilience that have direct parallels in audio signal processing. These sophisticated communication pathways can serve as models for dynamic signal routing in audio processing.

Third, the project is motivated by the desire to create instruments that foster specific modes of creative engagement, namely exploration, wonder, and openness to the unexpected. Many electronic music tools emphasise control and precision at the expense of discovery and surprise. By incorporating the emergent behaviours of natural systems, we can develop instruments that maintain a balance between player intention and system autonomy, creating spaces for unexpected musical moments and serendipitous discovery.

Finally, this work is motivated by the belief that biomimetic approaches to instrument design can promote a more holistic relationship between musicians, technology, and the natural world. By creating instruments that embody ecological principles, we invite musicians to engage with concepts of interdependence, resource distribution, and adaptive behaviour, concepts that extend beyond music making into broader ecological awareness.

1.2 Project Goals

This project aims to achieve several interconnected goals that span technical development, artistic exploration, and conceptual advancement in the field of biomimetic instrument design:

- **Develop a Functional Prototype of a Forest-Inspired Audio Processor**: Create a working delay-based audio effect system that embodies the principles of forest ecosystems, particularly focused on mycelial networks as a model for dynamic signal routing. This processor will serve as both a practical tool for musicians and a proof-of-concept for biomimetic approaches to audio processing.

- **Establish a Framework for Ecological-to-Audio Parameter Mapping**: Formulate coherent and musically meaningful relationships between ecological concepts (nutrient exchange, energy harvesting, network connectivity) and audio processing parameters (delay times, filtering, and amplitude modulation). Ideally, this framework should be extensible to other biological systems beyond forest ecosystems.

- **Design an Intuitive Interface that Communicates Ecological Concepts**: Create a user interface that not only facilitates interaction with the audio processor but also educates users about the underlying ecological principles. The interface should visualise the state of the system in ways that make the connection between biological processes and audio manipulation transparent and intuitive.

- **Foster Modes of Creative Engagement that Encourage Exploration**: Structure the instrument's behaviour and interface to reward curiosity, experimentation, and a willingness to surrender some control to the system's autonomous behaviours. The goal is to create an instrument that surprises and delights its users, encouraging them to explore unfamiliar sonic territories.

- **Document and Articulate Design Principles for Biomimetic Instruments**: Throughout the development process, identify and codify design principles that can guide future work in biomimetic instrument creation. These principles should address the issues of conceptual integrity, user experience, technical implementation, and ecological fidelity.
- **Evaluate the Effectiveness of Biomimetic Approaches in Musical Contexts**: Develop and apply criteria to assess how well the biomimetic instrument reaches its musical and conceptual goals. This evaluation should consider both technical performance and the qualitative experience of musicians who interact with the system.
- **Contribute to Broader Dialogues About Human-Nature-Technology Relationships**: Position this work within larger conversations about our relationship with natural systems and how technology might serve as a bridge rather than a barrier to ecological awareness. The project should demonstrate how technological creation can be informed by and respectful of natural processes.
- **Support Ecological System Education Through Musical Experience**: Leverage the inherent engagement of musical creation to help users develop an intuitive understanding of complex ecological processes. The experience of playing the instrument should leave users with a deeper appreciation of the sophisticated behaviours of forest ecosystems.

These goals reflect an integrated approach that recognises the technical, artistic, philosophical, and educational dimensions of biomimetic instrument design. The success of the project will be measured not just by the creation of a novel audio processor, but by its capacity to transform how musicians think about their relationship to technology and the natural world.

1.3 Research Problems

This project addresses several interconnected research problems at the confluence of audio processing, interaction design, and biomimetic systems:

- **Parameter Mapping and Translation**: How can we meaningfully translate ecological processes, such as nutrient exchange, energy harvesting, and mycelial network dynamics, into audio processing parameters? What mappings create the most intuitive and musically expressive relationships between biological concepts and sonic outcomes?

- **Dynamic Adaptation vs. Predictability**: How do we balance the desire for instruments to exhibit lifelike adaptive behaviours while maintaining sufficient predictability for musical expression? What degree of autonomous behaviour enhances rather than hinders the creative process?

- **System Representation and Interface Design**: How can we visually and physically represent complex ecological systems in ways that facilitate intuitive interaction? What interface elements best communicate the state of the underlying biomimetic system to the musician?

- **Temporal Scaling**: Natural processes operate on vastly different timescales than musical performance. How do we appropriately scale biological processes (which might take days, months, or years) to function within the time frame of musical performance (seconds or minutes)?

- **Network Topology and Signal Routing**: How can we implement signal routing architectures that mirror the adaptive, contextual behaviours of mycelial networks? What rules govern the establishment, strengthening, or pruning of connections in these audio networks?

- **Evaluation Metrics**: By what criteria do we evaluate the success of biomimetic audio processes? Is fidelity to biological models more important than musical utility? How do we measure the capacity of these systems to encourage exploration and wonder?

- **Conceptual Integrity vs. Usability**: How do we maintain the conceptual integrity of the biomimetic approach while ensuring the instrument remains accessible and usable? When are simplifications or abstractions of natural systems justified for the sake of musical expression?

By addressing these research problems, this project aims to develop not just a novel audio processor, but a framework for thinking about instrument design that bridges the gap between technological innovation and ecological awareness, creating tools that invite musicians to explore the rich, interconnected patterns that characterise both natural systems and musical expression.

Chapter 2

Problem Analysis

The Effective Disconnect

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The disconnect between human technology and natural systems represents a challenge in contemporary society, which is also reflected in instrument design trends. Although nature exhibits sophisticated adaptive behaviours, self-organisation, and adaptive intelligence, our digital audio tools remain largely static, predictable, and divorced from the dynamic principles that govern living systems. This chapter analyses how biomimetic approaches can inform the development of more responsive and ecologically inspired musical instruments.

"The fact that we lack the language skills to communicate with nature does not impugn the concept that nature is intelligent, it speaks to our inadequacy for communication."

- Paul Stamets

2.1 Background

The relationship between technology and nature has been fundamentally shaped by reductionist thinking that views natural systems as collections of discrete, analysable components rather than interconnected, adaptive networks. This perspective has profoundly influenced digital audio processing, where effects are typically conceived as isolated units with fixed parameters that operate independently of their musical context. A delay unit processes input according to predetermined settings, filters maintain static frequency responses regardless of the musical material they encounter. This is in stark contrast to the behaviour of ecological systems. A forest responds differently to a flood as opposed to a rain shower. The forest as an acoustic space is inherently adaptive, contextual, and alive in ways that digital reverb algorithms rarely attempt to emulate.

Recent advances in ecological research have revealed the sophisticated communication networks that exist beneath the forest floors. The mycorrhizal networks studied by researchers like Suzanne Simard[2] and futher distilled for the general public by Merlin Sheldrake[3] demonstrate that trees and fungi form complex partnerships where nutrients, water, and chemical signals are exchanged based on need, availability, and environmental conditions. These networks exhibit remarkable properties including resource redistribution, early warning systems for environmental threats, and adaptive routing that strengthens frequently used pathways while allowing unused connections to decay.

The principles governing these biological networks offer compelling models for audio processing systems. Resource allocation in mycelial networks parallels signal routing in audio processors, where computational resources and signal paths must be managed dynamically. The adaptive strengthening and pruning of biological connections mirrors the potential for audio routing systems that learn from usage patterns and musical context. The contextual responsiveness of natural systems suggests possibilities for audio processors that respond not just to immediate input characteristics but to longer-term patterns and environmental conditions.

This project investigates how these adaptive behaviours can inform the development of "living" musical instruments, proposing more "organic" inner workings, as well as interactions with technology. The research focuses specifically on the intersection of ecosystem dynamics and audio processing, developing a novel approach to instrument design that mirrors natural systems' responsiveness to both environmental conditions and internal state (which can be considered to be the system's memory).

2.2 Approach

Through the lens of an experimental audio processor (called *Sporadic*), biological concepts such as growth rates, network connectivity, and resource distribution are examined as foundations for ecological understanding that can be translated into musical parameters. The processor serves as both a practical tool for musicians and a research platform for exploring how biomimetic principles can create more intuitive and expressive electronic instruments that exhibit lifelike behaviours in response to player input.

The creative mission of Sporadic is to foster a sense of wonder and environmental appreciation while maintaining conceptual integrity and the ability to surprise and engage users. This requires solving several interconnected challenges, including meaningful parameter mapping between the ecological and audio domains, temporal scaling of biological processes for musical performance, and interface design that communicates complex system states intuitively.

The project must demonstrate that biomimetic approaches can enhance rather than complicate musical expression, creating instruments that reward exploration while remaining sufficiently intuitive for intentional creative work. Success after long-term use will be measured not only by technical innovation, but by the capacity to transform how musicians think about their relationship with technology and the natural world.

The methodology will focus on examining how forest nutrient exchange networks can serve as models for adaptive audio routing systems, where signal paths evolve based on input dynamics and system state. Rather than simply creating digital simulations of biological processes, the approach involves translating fundamental ecological principles into meaningful musical parameters and interactions.

The research approach balances theoretical investigation with practical application, ensuring that ecological concepts are not merely imposed upon audio processing but are integrated in ways that enhance musical expression. This requires careful consideration of temporal scaling, parameter mapping, and interface design to create instruments that are conceptually coherent and musically compelling.

2.3 Related Work

The intersection of biological systems and audio processing has been explored through several distinct approaches, each offering valuable insight while revealing the complexity of creating meaningful biomimetic instruments.

In the realm of algorithmic composition, researchers have drawn inspiration from various natural processes. Cellular automata have been used to generate musical structures that exhibit emergent behaviours similar to those found in biological systems[4][5]. The work of composers such as Iannis Xenakis explored stochastic processes inspired by natural phenomena[6], while more recent research has investigated genetic algorithms[7] for musical evolution and swarm intelligence for collaborative composition systems[8]. Artificial life approaches to music creation have explored how simple rules can generate complex musical behaviours. The field of evolutionary music has shown how populations of musical fragments can evolve over time, developing characteristics that parallel biological evolution. However, these approaches typically focus on composition rather than real-time audio processing, and they often prioritise algorithmic sophistication over musical expressiveness or user interaction.

Physical modelling synthesis[9] represents another approach to incorporating natural behaviours into audio processing. By simulating the physical properties of acoustic instruments and spaces, these systems achieve realistic responsiveness and contextual behaviour. However, physical modelling typically focuses on recreating existing acoustic phenomena rather than exploring novel forms of bio-inspired audio processing.

Adaptive and modulatable audio effects represent a growing area of research in which processing parameters respond to input characteristics. Audio compressors respond to input dynamics and reverbs that modify their characteristics based on input spectral content demonstrate such steps toward more responsive audio processing. However, these systems typically employ a relatively simple adaptation logic and lack the complex network or memory behaviours found in biological systems.

Machine learning approaches to audio processing have shown promise in creating systems that adapt and evolve based on input patterns. Neural networks trained on large datasets can exhibit behaviours that appear intelligent and responsive. However, these systems often operate as black boxes, making it difficult for musicians to understand or predict their behaviour, and they typically lack the conceptual coherence that comes from grounding design decisions in well-understood natural processes.

Recent work in biomimetic design has explored how natural systems can inspire technological innovation in various domains[10][11],[12],[13][14]. The field of biomimetics emphasises understanding the underlying principles of biological systems rather than simply copying their surface characteristics. This approach offers valuable guidance for creating audio processors that embody ecological principles rather than simply simulating ecological sounds.

The landscape of delay-based audio processing is a spectrum ranging from tra-

Figure 2.1: Examples of biomimetic design. Sources, clockwise from top left: [15], [14], [16], [17]

ditional engineering approaches to network-based designs that point towards the biomimetic possibilities explored in this project. Understanding these existing approaches helps clarify both the technical foundation and the conceptual departure that Sporadic represents. The following subsections focus on the use of delays in sound applications (Section 2.3.1) and some of the delay modules and effects that lent inspiration to the design of Sporadic (Section 2.3.2).

2.3.1 Classic Delays and Typical Use

The most direct application of delay processing involves creating discrete echoes that simulate natural acoustic reflections (see Figure 2.2 for a high-level view of the tape delay architecture). Early tape-based echo units such as the Watkins Copicat[18] and Roland Space Echo (shown in Figure 2.3) established the musical vocabulary of delayed repetitions, where the delayed signal creates rhythmic patterns and spatial depth. These systems introduced musicians to the creative potential of feedback, where delayed signals feed back into the delay line to create cascading repetitions that decay over time. The musical appeal of these early systems also stemmed from the inherent imperfections of their use of magnetic tape, including tape saturation, wow and flutter, and gradual degradation of repeated signals that added character and life to the processed sound.

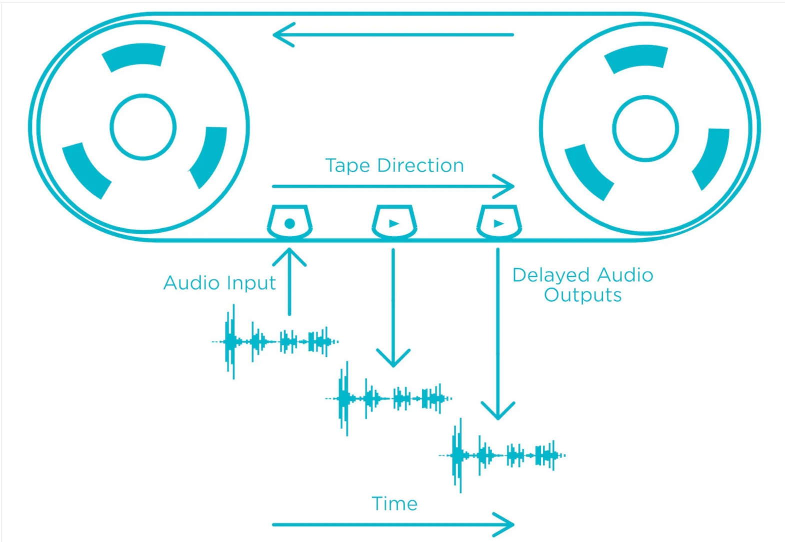

Figure 2.2: Tape Delay Conceptual Diagram. Source: [19]

These classic delay units operate as discrete processing blocks with fixed topologies. A typical delay pedal or digital delay unit processes incoming audio through a single delay line with adjustable parameters for delay time, feedback, and output level. These systems excel at providing predictable musical delay effects but remain fundamentally static in their behaviour. Even when parameters are modulated, the underlying signal path remains unchanged, limiting the potential for emergent or adaptive behaviours.

Figure 2.3: Roland Space Echo. Source: [19]

2.3.1.1 Modulated Delay Effects

When looking at modulated delay effects, it is important to remark that time-varying delays produce frequency-domain changes through the Doppler effect. When delay times change continuously, the pitch of delayed signals shifts up or down, and when these pitch-shifted signals combine with the original signal, they create the characteristic sweeping sounds of chorus, flanging, and phasing effects[20].

Chorus effects typically use delays in the range of 15-35 milliseconds with slow modulation to create the impression of multiple performers. The relatively long delay times place the delayed signals outside the range where they would be perceived as a single fused event, while the slow modulation simulates the natural timing variations that occur when multiple musicians play together. The result is a widening and thickening of the sound that mimics the acoustic manifestation of an ensemble without the phase cancelation that would occur with shorter delays.

Flangers employ much shorter delays of 1-10 milliseconds with more dramatic modulation to produce their distinctive swooshing character. These shorter delays place the effect in the range where delayed and direct signals are still perceived as a single event, but the comb filtering that results from their combination creates the characteristic spectral notches that sweep through the frequency spectrum. The dramatic modulation speeds used for flanging cause these notches to move rapidly, creating the dramatic sweeping effect that gives the processor its name.

These effects demonstrate how delays can transform from temporal processing into spectral processing through modulation, a principle that becomes particularly relevant when considering how biological systems might modulate delay networks based on environmental conditions. The key insight is that the same delay infrastructure can serve entirely different musical functions depending on the time scales and modulation strategies employed.

2.3.1.2 Karplus-Strong: Delays as Oscillators

The Karplus-Strong algorithm[21] represents one of the most elegant demonstrations of how delay lines can transcend their role as temporal processors to become the heart of synthesis systems. Developed in the early 1980s, this technique shows how a simple delay line combined with filtering can generate convincing plucked string sounds from nothing more than noise.

The basic Karplus-Strong algorithm works by filling a delay line with white noise, then allowing this noise to circulate through the delay while applying gentle low-pass filtering on each pass (as depicted in Figure 2.4). The delay time determines the fundamental frequency of the resulting tone, while the filtering gradually removes high frequencies, causing the initial harsh noise to evolve into a warm, plucked string-like sound that naturally decays over time.

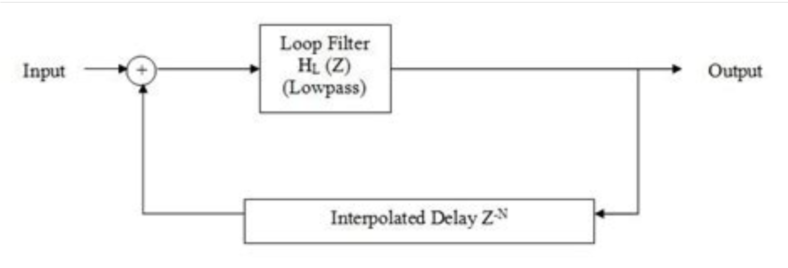

Figure 2.4: Basic Karplus-Strong Implementation

What makes Karplus-Strong particularly relevant from a biomimetic perspective is how it achieves complex, naturally-occurring behaviour through such simple means. The algorithm does not attempt to model the physics of string vibration directly; instead, it creates a feedback system that naturally develops the spectral and temporal characteristics we associate with plucked strings. The low-pass filtering serves multiple functions simultaneously: it removes the harsh edges from the initial noise burst, it causes the sound's amplitude to decay naturally over time, and it shapes the harmonic content, such that higher frequency content of the emulated oscillation decays quicker than the low frequency ones, in a way that mimics real string behaviour.

2.3.1.3 Granular Synthesis

Granular synthesis represents another domain where delay processing takes on more complex, network-like characteristics. In granular systems, audio signals are fragmented into small time windows or grains, typically lasting between 1 and 100 milliseconds, that can be delayed, reordered, and recombined in complex patterns.

The Curtis Roads approach to granular synthesis[22] often involves networks of delay lines where grains travel through different paths with varying delays, creating textures that exhibit both temporal and spectral complexity. Unlike traditional delay effects that maintain a fixed relationship between input and output timing, granular systems can scatter individual grains across time in ways that destroy the original temporal structure while creating new emergent patterns (such as the example in Figure 2.5 shows).

Figure 2.5: Granular Synthesis in Omnisphere

The temporal complexity that emerges from granular delay networks often exhibits characteristics that seem organic or lifelike, particularly when the network parameters evolve over time in response to processed audio. Grains may accumulate in certain regions of the delay network, creating dense clusters of activity that gradually migrate through the processing space, much like the way biological systems develop temporary organisational structures that emerge, persist, and dissolve based on environmental conditions.

2.3.1.4 Feedback Delay Networks

Feedback delay networks represent one of the more advanced applications of delay processing, particularly in the context of artificial reverb algorithms. These systems employ multiple delay lines connected in complex feedback matrices to simulate the dense, decorrelated reflections that characterise natural reverberation. The Schroeder reverb algorithm, developed in the 1960s, established the fundamental approach of using parallel comb filters and series allpass filters to create convincing spatial impressions[23]. The comb filters provide the basic resonant characteristics that simulate room modes and standing wave patterns, while the allpass filters add the decorrelation and density that make the artificial reverberation sound natural rather than metallic or harsh.

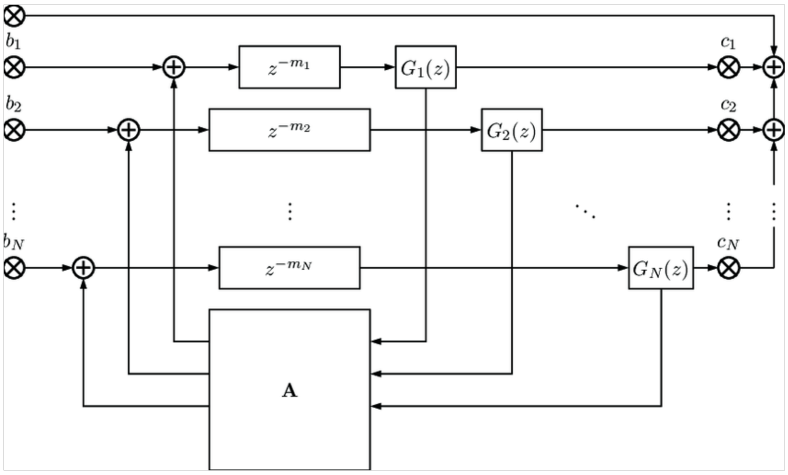

Figure 2.6: Block diagram of a generalized feedback delay network (FDN). Source: [24]

Modern reverb algorithms extend this concept through increasingly complex networks where delay lines interact through sophisticated routing matrices that can be time-varying and frequency-dependent. Some delay lines might be dedicated to early reflections that establish the apparent size and geometry of the space, while others contribute to the dense late reverberation that provides warmth and envelopment.

The mathematical elegance of feedback delay networks belies their ability to create complex acoustic behaviours through relatively simple recursive structures. Each delay line in the network contributes to the overall impulse response, and the interaction between multiple delay lines creates the dense, evolving texture that characterises natural acoustic spaces. The key insight for biomimetic applications is that these networks achieve their effectiveness through principles that parallel biological systems including redundant pathways, adaptive routing based on frequency content, and emergent behaviours that arise from the interaction of simple components.

Delay lines serve as fundamental building blocks in audio processing, appearing in contexts far beyond the obvious echo effects that most musicians first encounter. The ubiquity of delay-based processing throughout audio engineering demonstrates the versatility of this basic concept, while revealing opportunities for more sophisticated, biology-inspired implementations.

2.3.2 Modern Delay Implementation Examples and Inspiration

Contemporary delay designs excel when the focus is on modulation and feedback/ cross-patching capabilities. Examples of such units are the Audio Damage Other Desert Cities [25] VST plugin and the Make Noise Mimeophon[26] Eurorack module. The former has a strong emphasis on creating delay textures that evolve continuously and the latter offers morphing between different delay configurations. These instruments hint at the potential for delays that exhibit more complex behaviours. The Mimeophon's morphing between different delay configurations offers glimpses of how delay topologies might evolve dynamically. This instrument employs a sophisticated interpolation system that can smoothly transition between entirely different delay architectures, from simple single-tap echoes to complex multitap patterns with intricate feedback routing. The morphing process is controlled by continuous parameters that can be modulated in real-time, creating delay systems that can transform their fundamental architecture based on musical context or performance gestures.

Figure 2.7: Modern Delay-Based Instrument Examples. Sources, clockwise from top left: [25], [26], [27], [28]

More sophisticated delay architectures such as the Verbos Multi-Delay[28] or the Make Noise Strega[27] begin to suggest feedback delay network-like possibilities. The former aims to provide "effects that become a fundamental part of the sound" and rhetorically questions whether "a guitarist would be asked to not use pedals". The latter does not provide multiple delay lines with cross-patching capabilities directly to the user. Instead, the Strega puts emphasis on dirty, internal evolving delay lines, particularly suggesting how delay systems might develop character and personality over time. The delay implementation deliberately introduces nonlinearities, saturation, and instabilities that cause the delay characteristics to drift and evolve during use.

Regardless how much these systems encourage fusing the input sound's character with the delay system behaviour, they still require manual reconfiguration of signal paths and do not exhibit the autonomous evolution that characterises living networks. The musician must explicitly create and modify connections rather than allowing the system to develop its own pathways based on usage patterns and environmental conditions.

The concept of "unreliable" or evolving delay systems finds expression in instruments such as the Soma Cosmos[29], which deliberately introduces unpredictability and evolution into the delay process in ways that challenge conventional notions of what audio processing equipment should do. The Cosmos functions as what its creators describe as an "working meditative states through music," acknowledging that perfect reliability, while useful for certain applications, may not always serve creative expression in the most interesting ways.

Figure 2.8: Soma Cosmos

The Cosmos suggests how delay systems might develop their own behaviours and tendencies, creating partnerships with musicians rather than simply executing their commands. The Cosmos achieves its unreliability through a combination of digital processing logic and algorithmic decision-making that introduces controlled randomness into the delay process. The system might choose to record certain passages while ignoring others, or it might process recorded material through different delay paths based on internal criteria that are not fully predictable or controllable by the user. This creates a sense that the instrument has its own intentions and preferences, making musical decisions in collaboration with the performer rather than simply responding passively to control inputs.

What makes the Cosmos paradigm particularly relevant to biomimetic delay design is its demonstration that musical value can emerge from systems that exhibit autonomous behaviour. The instrument's unpredictability is not arbitrary chaos, but rather a form of intelligent randomness that responds in a characteristic manner that becomes familiar and musically useful over extended periods of use. Patience and curiosity are rewarded.

2.4 Problem Statement

Given the current limitations in digital instrument design and the aim to create more adaptive and ecologically-conscious creative tools, the core problem this project addresses can be stated as follows:

Contemporary digital audio processing systems often operate according to static, predetermined parameters that fail to capture the adaptive, contextual, and interconnected behaviours that characterise natural systems. This results in instruments that, while precise and reliable, lack the organic responsiveness and emergent complexity that could foster deeper creative exploration and ecological awareness. How can we approach creating instruments and effects that illustrate naturally occurring patterns as sound manipulation, while using audio processing as a medium to narrate natural processes?

2.5 Design Requirements

To navigate the problem space and address the research questions outlined in Section 1.3, several key requirements must be met. These requirements emerge from the need to balance ecological fidelity with musical utility, ensuring that the biomimetic approach enhances rather than restricts creative expression.

These requirements can be split into two categories: a) functional capabilities (what the system must do) and b) the quality attributes and constraints (how the system should be built and evaluated), also known as non-functional requirements. Together, these provide a clear framework for development and evaluation. The requirements are shown below:

2.5.1 Functional Requirements

1. **Audio Processing Capabilities**
    - Provide a delay-based audio processing engine.
    - Handle real-time audio input and output.
    - Support multiple simultaneous delay lines, variable delay times, feedback control, and filtering capabilities.
    - The processor must maintain audio quality standards suitable for professional music production.
    - The system must support operation with audio latency as low as 10 milliseconds, ensuring suitability for live performance contexts where timing precision is critical.
2. **Adaptive Network behaviour**
    - The system must implement dynamic signal routing that mirrors mycelial network principles.
    - The network topology must evolve in response to musical input.
    - The network shall have the ability to establish new signal pathways based on input characteristics, strengthen frequently used connections, and prune unused pathways over time.
    - The system must maintain stability and prevent runaway feedback conditions.
3. **Ecological Parameter Mapping**
    - The system must translate biological concepts into meaningful audio parameters through well-documented mappings based on peer-reviewed ecological research.
    - Parameters to translate should include, but not be limited to, nutrient availability, growth rates, and network connectivity
    - The system must provide clear relationships between ecological concepts and audio outcomes that musicians can learn and exploit creatively.
4. **User Interaction Interface**
    - The system must provide input mechanisms that allow musicians to influence ecological parameters in musically meaningful ways.
    - The interface must support both direct parameter control and higher-level environmental conditions that affect system behaviour indirectly over longer time periods.

5. **Real-time Visualization**

    - The system must provide visual feedback that communicates the current state of the underlying ecological model.
    - The visual representation must update in real-time to reflect changes in the system state.

2.5.2 Non-functional Requirements

1. **Performance and Reliability**

    - The processor must operate with low latency appropriate for live performance.
    - The system must operate reliably in live performance contexts, providing predictable behaviour when needed while maintaining its capacity for surprise and emergence.
    - This includes stable operation under various input conditions, graceful handling of extreme parameter values, and consistent response to user input.
    - The graphical interface must be intuitive enough for musicians to understand system behaviour quickly while being detailed enough to support deeper exploration.

2. **Conceptual Integrity**

    - The system must maintain coherent relationships between ecological concepts and audio processing behaviours throughout all aspects of design and implementation.
    - Every feature must be justifiable in terms of the underlying biological model, ensuring that the biomimetic approach enhances rather than obscures the instrument's behaviour.
    - The system must avoid arbitrary mappings that undermine the conceptual foundation.
    - These mappings must be musically relevant, creating sonic changes that enhance rather than distract from musical expression.

3. **Musical Expressiveness**

    - The system must enhance rather than limit musical expression, providing musicians with new creative possibilities while maintaining intuitive control mechanisms.

- The ecological behaviours must translate into musically meaningful variations that support rather than distract from creative intentions.
- The system must reward exploration while remaining responsive to musician input.

4. **Educational Value**

- The system must communicate ecological concepts effectively, helping users develop intuitive understanding of forest ecosystem dynamics through musical interaction.
- The experience of using the instrument should leave musicians with greater appreciation for natural systems' sophistication and complexity.
- Educational goals must integrate seamlessly with musical functionality without creating pedagogical obstacles to creative use.

5. **Biological Timescale Adaptation**

- The system must successfully adapt biological processes that naturally occur over days, seasons, or years to timescales appropriate for musical use.
- Network evolution and ecological changes must occur at rates that create perceivable musical development within minutes while maintaining biological plausibility.
- Users must be able to adjust temporal scaling factors to match different musical contexts, from real-time performance requiring immediate responsiveness to compositional work that can accommodate slower development over extended sessions.

6. **Scalability and Extensibility**

- The design must support future expansion to incorporate additional ecological concepts and audio processing techniques.
- The underlying architecture must be flexible enough to accommodate new biological models and processing algorithms without fundamental redesign.

These requirements establish the criteria against which the project's success will be evaluated (as presented in Section 5), ensuring that Sporadic achieves both technical excellence and conceptual coherence while serving the practical needs of musicians and the educational goals of ecological awareness.

Chapter 3

Design Manifesto

A Light for Attracting Attention

AI-generated photo (©DALL-E)

The creation of biomimetic instruments demands a philosophical framework that guides the design process, one that respects the complexity and integrity of natural systems while translating them into meaningful musical tools. This manifesto articulates the principles that govern this project's approach to biomimetic design, establishing ethical and conceptual guidelines for the development process. The following sections discuss the core principles that crystallised while engaging with biomimickry, as well as reflections on the role of the designer more generally.

3.1 Core Principles

This section articulates the core principles that govern this project's approach to biomimetic design, establishing both ethical and conceptual guardrails for the development process. These principles move beyond simple imitation of natural features, aiming to allow the system to unfold naturally, avoid misrepresentation and decontextualization, and resist anthropomorphisation. By outlining these foundational ideas, this section sets the stage for the practical implementation of Sporadic, ensuring that the design remains aligned with the overarching goals of fostering exploration, wonder, and a deeper connection with the natural world.

3.1.1 Do Not Coerce

Natural systems unfold according to their own internal logic, shaped by millions of years of evolution and adaptation. When designing instruments inspired by these systems, we must resist the temptation to force these systems into predetermined forms that serve an immediate purpose, but devoid them of their essential character.

This means *preserving the inherent complexity* of natural systems, with caution exhibited in order to avoid oversimplification for the sake of convenience. Natural systems are inherently messy, interdependent, and resist reduction to simple cause-and-effect relationships. Thoughtful designs should honour this complexity. Biomimetic instruments should embrace multifunctionality rather than serve a singular purposes.

Good design should also *create space for emergence*, allowing the system to reveal its own patterns and behaviours, rather than being constrained to produce only expected or desirable outcomes. Incorporate enough freedom that unexpected properties can emerge and flourish. Additionally, recognise that nature rarely creates single-purpose solutions: a mycelial network simultaneously transports nutrients, facilitates communication, provides defence, and aids decomposition within an ecosystem.

Furthermore, it is essential to acknowledge that natural systems exist in constant flux, continuously seeking equilibrium, while never achieving perfect stasis. Biomimetic instruments should embody this *dynamic balance* rather than to enforce rigid stability, allowing for the natural ebb and flow that characterises living systems.

3.1.2 Do Not Misrepresent

When translating natural systems into technological forms, there is a constant risk of misrepresentation, of distorting the essential character of these systems either through decontextualization or through selective attention to certain features at the expense of others.

To avoid this pitfall, we must maintain *contextual integrity*, resisting the temptation to extract isolated features from natural systems without acknowledging their place within larger ecologies. The mycelial network, for instance, cannot be truly understood apart from the trees it connects, the soil it inhabits, and the climate in which it exists.

We must also approach our work with *historical respect*, recognising that the systems inspiring us have histories extending far beyond human experience. The mycelial networks beneath our feet evolved over millions of years before humans walked the Earth, and our representations should honour this temporal depth rather than reducing them to mere contemporary tools.

When translating natural processes into musical timescales, appropriate *temporal and spatial scaling* is necessary. What might take months in a forest ecosystem may be compressed to seconds in musical terms, yet this compression should be done with awareness and integrity, transparent with regard to the transformation taking place.

Finally, be honest about which aspects of the natural system are not captured in the model. No technological system can fully represent the complexity of natural processes, and *acknowledging these limitations* is part of creating an honest representation.

3.1.3 Do Not Anthropomorphize

Perhaps the most insidious temptation in biomimetic design is to project human qualities, intentions, and frameworks onto non-human systems. This anthropomorphising tendency not only misrepresents these systems but can also limit our ability to learn from their truly alien and remarkable properties.

To avoid this, we must *resist attributions of will*. Avoid language and design choices that imply purposeful intention where none exists. A forest ecosystem does not "decide" to distribute resources; it follows chemical gradients and evolutionary adaptations.

Be cautious about describing natural processes in terms of "intelligence" or "decision-making" unless these terms are carefully qualified. The the "Wood-Wide Web" (a term which is in itself an anthropomorphisation) communicates, it does not "think" in human terms, and the design should reflect this distinction. Instead, we should embrace non-human logics, allowing our instruments to operate according to principles that may initially seem counter-intuitive from a human perspective. The patterns of fungal growth follow mathematical principles that may feel foreign but contain their own consistent internal logic.

Finally (and crucially), strive to *balance user agency and system autonomy*, creating a relationship between musician and instrument that neither surrenders completely to user control nor becomes an impenetrable "black box" with a mind of its own. The ideal biomimetic instrument maintains a dynamic conversation between human creativity and system behaviour, respecting the integrity of both participants in this unusual dialogue.

3.2 The Designer's Role: Illuminating the Unseen

In creating tools and experiences, designers wield significant power to shape attention, understanding, and engagement. This power comes with profound responsibility, particularly when addressing complex systems like forest ecosystems that are simultaneously fundamental to life on Earth and largely invisible to everyday human perception. The designer's role extends far beyond creating functional objects; it encompasses directing awareness toward critical aspects of our world that might otherwise remain unnoticed or underappreciated.

3.2.1 Pointing the Flashlight

The designer serves as a guide, directing attention toward specific domains of knowledge and experience, essentially "pointing the flashlight" at areas they believe deserve focused consideration. In the context of this project, the flashlight illuminates the invisible networks beneath our feet, the complex interdependencies of forest ecosystems, and the profound importance these systems hold for our collective future. This directed attention is not neutral; it represents a deliberate choice to elevate certain forms of knowledge and experience over others.

This role becomes particularly significant for addressing environmental concerns and climate anxiety. Rather than approaching these topics through frameworks of guilt, accusation, or paternalism, the designer can transform engagement by fostering fascination, curiosity, and wonder. By creating instruments that translate ecological processes into tangible, interactive experiences, designers can shift the narrative around environmental awareness from one of duty or fear to one of discovery and connection.

The designer's responsibility is to create this initial entry point: to provide what might be, for some users, their first conscious encounter with the complexities of mycelial networks or forest communication systems. Even a brief moment of realisation: "Oh, there is this hidden world out there that has existed for millions of years" can plant a seed of curiosity that develops into deeper engagement over time. The designer thus becomes an educator in an indirect but powerful sense, not lecturing or preaching, but creating conditions where users can develop their own understanding through direct engagement with translated natural systems.

3.2.2 Natural Awareness Through Wonder

While creating functional tools, the designer simultaneously encodes values, perspectives, and possibilities into these tools. Each design decision carries implicit messages about what is worth attending to, what relationships matter, and what modes of engagement are possible or desirable.

In the case of Sporadic, the basic perspective is that natural systems contain sophisticated patterns worthy of our attention and respect. These invisible processes can be made perceptible through thoughtful translation. Music, and the music-making process, can serve as a medium for understanding complex ecological relationships.

Climate anxiety represents a particular challenge that has been continuously present in the refinement of this design. How can we address urgent environmental concerns without triggering disengagement through fear, guilt, or overwhelm? This project suggests an alternative approach: nurture environmental awareness through wonder rather than warning and alarm.

By creating instruments that translate ecological principles into musical experiences, the designer creates opportunities for users to develop intuitive, embodied understanding of natural systems. This understanding may, in turn, foster a sense of connection and care that motivates environmental stewardship more effectively than abstract warnings or dire predictions.

The designer's responsibility here is delicate: to create experiences that honestly represent the complexity and fragility of natural systems without either minimising environmental concerns or inducing paralysing anxiety. The goal is to create what the environmental philosopher David Abram calls "a sense of the world as having depths that exceed our human projects": a recognition that may serve as the foundation for more sustainable relationships with the more-than-human world.

3.2.3 Balancing Guidance and Freedom

While pointing the flashlight in particular directions, the designer must simultaneously avoid constraining the user's freedom to explore and create. Good design suggests without imposing, guides without dictating. The designer creates a "departure point", a scene or territory to inhabit at the beginning of the journey, while leaving users free to chart their own path from that initial position.

This balance applies both to the instrument's functionality (allowing for unexpected musical discoveries) and to its conceptual framing (suggesting ecological connections without prescribing how users should understand or relate to them). The designer creates conditions for discovery rather than dictating conclusions.

In this way, the designer's responsibility extends to creating spaces of possibility rather than merely functional objects, spaces where users can develop their own relationships with both the immediate tool and the natural systems it references. The ultimate measure of success is not whether users adopt the designer's perspective, but whether the design enables users to develop richer, more nuanced perspectives of their own.

3.3 Putting It All Together

These principles translate into specific design practices throughout the development process:

- **Be Curious**: Approach the design process as an exploration rather than an imposition of will. Allow yourself to be surprised by what emerges from the system you're creating.
- **Document Faithfully**: Maintain clear documentation of how natural processes are translated into audio parameters, acknowledging both the strengths and limitations of these translations.
- **Test Against Reality**: Regularly compare the behavior of your instrument against the natural system it claims to represent. Does it capture essential aspects of that system's behaviour? Where does it diverge, and is that divergence justified?
- **Seek Balance Between Abstraction and Concreteness**: Find the appropriate level of abstraction that preserves key properties of the natural system while translating them into usable musical parameters.
- **Value Interdependence**: Design the instrument as a system of interconnected parts rather than isolated components, reflecting the interdependent nature of ecological systems.

3.4 A Living Document

This manifesto is itself a living document, subject to growth, adaptation, and refinement as the project develops. Just as natural systems evolve through interaction with their environments, these design principles will be tested, challenged, and enhanced through the practical work of instrument creation.

By articulating these principles at the outset, not just a set of guidelines for development is established, but a philosophical foundation that orients the work within larger questions about humanity's relationship with the natural world. The biomimetic instrument becomes not just a tool for music-making, but a medium through which musicians can develop a more intuitive understanding of ecological principles and perhaps a deeper appreciation for the complex, interdependent systems that sustain life on our planet.

Chapter 4

Implementation

Construction Time Again

Double Decker Living Root Bridge (image source: web)

This chapter details the work undergone during the thesis, presented here split into four themes that coincided with significant milestones in the process. The following subsections are organised as follows: Section 4.1 presents the outsized impact of the participation in the Nordic Summer University Symposium in March. The very early stage mock-up of the idea presented there matured over time, based on a set of foundational biological concepts laid out in Section 4.2, together with the parameter mapping used for Sporadic. The final two sections tackle the technical work related to the translation of ecosystem dynamics and scale to musical use, as well as the interface design. This is split into a short overview of the tech stack, form factor and overall architecture (Section 4.3) and a deeper dive in Section 4.4.

"*And if you'd do it all again*
Would it end up just the same?
Just because lines settled now
Can't mean this sand won't run"

4.1 First Quarter: Conceptual Refinement

The initial stage of this project represented a period of intense conceptual development, where the core ideas behind the forest-inspired audio processor began to take definitive shape. Although the biological inspiration had been present from its inception, it was during this phase that clear connections between ecosystem dynamics and audio processing parameters emerged as viable design elements. Participation in the Nordic Summer University (NSU) Symposium served as both a catalyst and a testing ground for these emerging ideas. With the design at the intersection of biological systems, audio processing, and interface design, it was particularly relevant to the symposium's themes related to agency, social participation, and interdependence.

This period was characterised by an intentional balancing act between technical implementation concerns and the philosophical underpinnings of biomimetic design. Questions concerning the meaningful translation of natural phenomena into musical parameters while avoiding superficial imitation became central to the design process. The symposium provided an ideal forum to air these questions with an interdisciplinary audience interested in the intersections of technology, nature, and creative expression. It ended up being an important juncture point in the instrument design process.

4.1.1 In Search of the Future Imperfect

The symposium's exploration of "Cybioses: Life in the Future Imperfect" [1] created a rich contextual framework to position Sporadic within the broader discussion on human-nature-technology relationships. Particularly striking was how the recurring themes of interdependence and nonlinearity in other presentations validated core aspects of the instrument's conceptual foundation.

During discussions following my presentation, several participants highlighted the potential of the project to serve as what one attendee called a "sensory bridge" between abstract ecosystem concepts and embodied musical experience. The forest-inspired delay effect was recognised not merely as a novel audio processor but as a potential pedagogical tool that could foster ecological awareness through creative engagement. This perspective aligned with Özge Kelekçi's presentation on "Artificiality As an Emergent Process," which emphasised relational ontology and the

[1] NSU Circle 2: Cybioses – Life In The Future Imperfect

dangers of extractive approaches to biomimicry that "overstate functionality" while decontextualising natural systems.

Particularly influential was the symposium's emphasis on "listening as a method" for understanding complex systems. Drawing parallels to Pauline Oliveros' Deep Listening [30] practice mentioned in Krista Dintere's presentation, participants suggested that Sporadic could function as a tool for what one attendee described as "ecological listening" – attending not just to individual sonic elements but to the relationships and emergent properties that arise from their interaction. This perspective reinforced the importance of designing the instrument to reveal the invisible interconnections within forest systems rather than simply mimicking their surface characteristics.

The symposium's critical discussions around technology and participation also prompted a refinement of the user interface design philosophy. As one presenter noted, true engagement involves "not offloading decision making to computers" but rather creating systems where human agency remains central while embracing "the unpredictability of natural phenomena." This tension between control and emergence became a guiding principle for subsequent parameter mapping decisions in Sporadic.

Perhaps most significantly, the symposium reinforced an intuition that was not fully articulated at the time: that the project exists not merely as a technical achievement but as a form of "epistemic world-building" that invites users to reimagine their relationship with technology and natural systems. The recurring theme of technology's role in contributing to what one presenter called a "deficit of wonder" highlighted the importance of designing for curiosity and discovery rather than mere efficiency or technical innovation.

4.1.2 From Critique to Implementation

Following the symposium, the conceptual foundation of Sporadic underwent several important refinements. Early mockups presented at NSU, while conceptually sound, required translation into implementable design specifications. The feedback received helped clarify which aspects of forest ecosystems would be most meaningful to model in an audio context. Three key insights emerged from this phase of the project that would guide subsequent development:

First, the importance of temporal dynamics in modelling ecosystem processes. The symposium discussions highlighted how the varying timescales of natural processes, from rapid nutrient exchange to gradual forest growth, could create interesting musical possibilities if thoughtfully mapped to audio parameters. This led to the implementation of multiple interlocking timing systems within the delay network.

Second, the value of visible and invisible complexity. Several symposium participants noted how the visual representation of the mycelial network in the conceptual diagrams immediately conveyed the interconnectedness of the system in ways that would be difficult to communicate through sound alone. This observation informed the decision to develop a visual interface that would make these invisible connections within the audio processor visible to users.

Third, the significance of emergent behaviours. Discussions around complex systems theory reinforced the importance of designing parameters that interact in nonlinear ways, potentially creating sonic outcomes that could not be predicted from individual settings alone. This perspective reinforced the desire to design relational systems where interesting behaviours could emerge from simple interactions, based on relationships between live performance and system history.

These insights formed a bridge between the theoretical discussions at the symposium and the practical implementation work that would follow. Rather than attempting to directly translate all aspects of forest ecosystems into audio processing, the refined approach focused on capturing key relational dynamics that could create meaningful musical experiences while remaining true to the biological inspiration and not shying away from allowing Sporadic to be "messy", "untamed", "alive".

4.2 Full Moon: Biological Foundation

The second major milestone in the development of Sporadic has been to establish an ecological framework to operate under. While a large part of the biological analysis has been prepared and presented as part of the NSU Symposium (discussed in Section 4.1, its centrality to the development of the musical effect warrants a closer look here. What follows is a short overview of the forest ecology behaviours that are front and centre in Sporadic (Section 4.2.1) and the step-by-step breakdown into the main atomic components and their correlation to musically-relevant concepts (Section 4.2.2).

4.2.1 Forest and Mycelial Ecology 101

The world beneath our feet is a complex, dynamic system of communication and resource exchange, where fungi play a role far more nuanced than most imagine. Mycelial networks, the intricate, thread-like structures of fungal organisms, are not merely passive conduits of nutrients, but sophisticated, adaptive systems that represent some of nature's most ingenious solutions to resource management [31] [32].

Forests exist as intricate ecosystems where trees, fungi, and countless other organisms form interdependent relationships that have evolved over millions of years. At the heart of this ecosystem lies what mycologists have come to call the "Wood-Wide Web" [1] [33], a vast underground network of fungal mycelium that connects individual trees across forest floors, facilitating communication and resource sharing that transcends the apparent solitary nature of individual organisms[34].

These networks operate with remarkable intelligence without centralised control. They respond dynamically to changing conditions, directing resources where they're most needed [31] and adapting their structure to optimise resource distribution across time and space. This natural system demonstrates principles of emergence, resilience[35], and temporal sensitivity that have profound implications when translated to the domain of audio processing.

What makes mycelial networks particularly fascinating as a model for audio effects is their gradient-driven nature. Unlike digital systems that operate with precise, binary logic, mycelial networks function through osmotic principles: nutrients flow, molecule by molecule, from areas of high concentration to areas of low concentration, creating dynamic equilibrium states that constantly shift in response to changing inputs and environmental conditions [36]. This analog, continuous-state behaviour creates rich terrain for modelling dynamic audio processing algorithms.

Furthermore, mycelial networks exhibit a quality of memory and adaptation. The pathways that form between trees are not static; they strengthen with use and atrophy with disuse, creating a system that evolves based on its history of activity [37] [31]. This temporal dimension introduces possibilities for audio effects that "learn" from input patterns, developing unique characteristics based on how they're played rather than simply processing signals according to fixed parameters.

4.2.2 Musical Atoms

To translate these complex ecological relationships into musical parameters, we must break down the forest ecosystem into its component processes and understand how each might influence the behaviour of an audio effect. The following sections examine key biological processes and their proposed musical analogies. Figure 4.1 depicts an early conceptual diagram that can serve as a visual guide in the subsequent discussion.

4.2.2.1 Solar Energy Harvesting

Trees capture solar energy through photosynthesis, converting light into chemical energy that fuels all forest processes. This energy capture is the fundamental input that drives the entire ecosystem. The rate and efficiency of energy capture vary with factors such as canopy position, leaf surface area, and seasonal conditions. Trees at the forest edge typically receive more direct sunlight than those in the understory, creating natural disparities in energy availability.

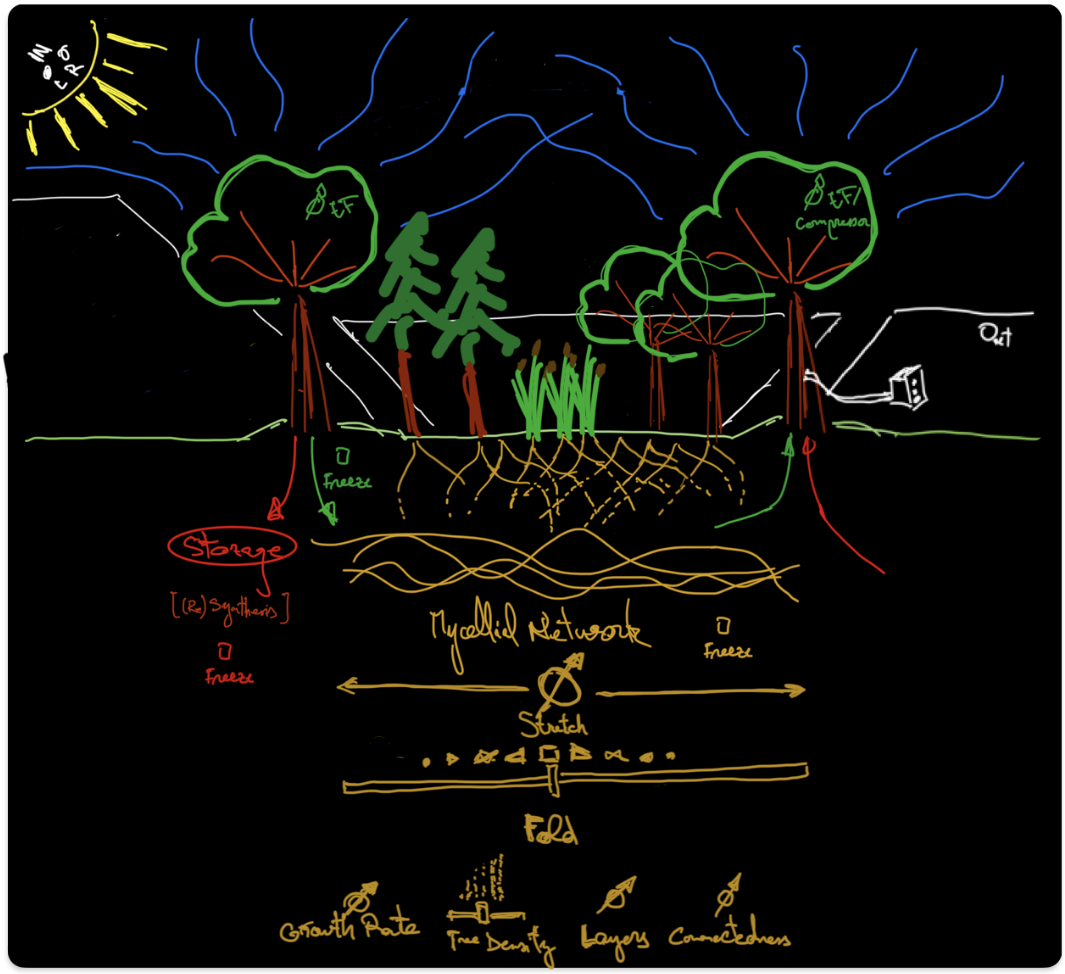

Figure 4.1: Sporadic Concept Diagram

Musical Interpretation. In Sporadic, the audio input serves as the solar energy. It is the raw material that powers the entire system. Just as sunlight enters the forest canopy and is transformed into usable energy, the incoming audio signal is the initiating force that sets the entire effect in motion. The amplitude of the input signal determines the "energy" available to the system. Thus, louder signals provide more "energy" to drive network processes.

The spectral content is analogous to different wavelengths of light, with certain frequencies potentially processed differently by the system, as will be detailed in the next paragraphs. The tree on the left side of the conceptual diagram is depicted as an envelope follower whose threshold (related to tree size) determines how much energy enters the root system and mycelial network. This creates a dynamic effect modulated by the volume and velocity of playing, where only signals exceeding a certain threshold enter the full processing chain. Transient content (similar to sudden sunlight breaking through cloud cover) will affect how quickly energy enters the system.

4.2.2.2 Energy Storage and Distribution

Trees do not immediately use all the energy they capture. Like mammals, they've evolved sophisticated storage systems that operate at different timescales. Short-term storage occurs near the leaves, where soluble glucose provides ready access to energy. Long-term storage is placed at the root level, where more complex carbohydrates and minerals are stored for seasonal use [33]. This multi-tiered storage system allows trees to maintain operation during periods of reduced sunlight and respond to changing energy demands. This is similar to the way glucose used moment-by-moment is present in the bloodstream, while glycogen in the muscles and liver is a form of short-term storage. Adipose tissue completes the picture as the long-term storage form in mamalian organisms.

Musical Interpretation. In audio terms, this storage principle translates to various forms of signal buffering and envelope shaping. The metabolic energy and short-term storage correlate to the attack/decay characteristics of the processed signal, determining immediate response to input. The system does not merely pass signals through. Instead, it stores and releases energy according to rules that mimic a tree's metabolism.

The envelope follower threshold and attack/delay rates control how much of the energy passes down to the root level. The larger the tree, the higher the envelope follower threshold and the slower the attack rate (and quicker decay). This reflects the higher metabolic rate of such trees, which require more energy to satisfy their instantaneous energy requirements. Conversely, smaller trees have lower thresholds for energy requirement satisfaction, and the envelope follower's attack is shorter, with a longer decay.

This creates a more organic response to player input than traditional delay effects, with signals building up and dissipating in ways that feel alive rather than mechanical. The movement between storage systems creates soundscapes with shapes that evolve over time.

The "Storage" element in the conceptual diagram (marked in red) represents each tree's root-level long-term energy storage. This allows trees to conserve resources during difficult conditions, but also allows them to take a stake in the forest nutrient marketplace in times of (relative) abundance, as will be discussed in the following subsection.

4.2.2.3 Root Systems Tapping into the Mycelial Network

Tree roots form the interface between individual trees and the larger mycelial network. Through specialised structures called mycorrhizae, trees establish symbiotic relationships with fungi, exchanging carbon compounds for nutrients the fungi gather from the soil [38] [39]. This connection point represents a noteworthy negotiation between individual and community needs, with trees able to regulate how much they contribute to and draw from the shared network.

The physical structure of roots creates complex geometries that influence how resources flow into and out of the tree. Some species develop deep taproots, while others create shallow, spreading root systems, each strategy creating different relationships with the mycelial network [35].

Musical Interpretation. In Sporadic, this root interface becomes a critical juncture where individual signals enter a shared processing space. This connection point involves filters that determine which frequency components enter the network, akin to how roots selectively absorb certain nutrients (as will be discussed in more detail in Sections 4.2.2.4 and 4.2.2.5).

The transition from individual tree to shared network creates opportunities for cross-modulation between multiple audio streams where multiple sources (of energy storage) are present. Like trees in a forest sharing root space, separate signals can influence each other's processing in subtle or dramatic ways depending on system parameters.

In the diagram, the connection points between tree roots and the yellow mycelial network represent these interfaces. The green and red arrows indicate the bidirectional flow between individual trees and the network, allowing for complex feedback relationships that evolve over time. Not all colonies will be tapped into by each tree root system, further complicating the relationship between spatio-temporal relationships between trees and, as will be shown, the frequency content of the delay mosaic.

4.2.2.4 Mycelial Network Mediating Nutrient Exchange

The mycelial network itself is perhaps the most fascinating component of the forest ecosystem. Operating on principles of osmosis, nutrients move along concentration gradients from areas of abundance to areas of scarcity[36]. This movement is not instantaneous, it occurs through a time-based fluid propagation process that is considerably slower than electrical signals or light.

Network topology affects propagation paths, with some connections strengthening through use [31]. Redundant pathways create multiple routes for nutrients to travel, resulting in dispersive effects in which the same nutrient may arrive at different times through different paths[35] [40].

Different nutrients may move through wildly different physical paths, helped along by mycelial colonies with different specialisation. This is discussed in more detail in Section 4.2.2.5.

Musical Interpretation. This complex exchange network forms the heart of Sporadic's delay and modulation architecture. Signal propagation follows gradient-like principles, where stronger acoustic energy reserves trigger movement towards weaker catered ones.

The mycelial network acts as a meta-delay system, where multiple taps create a mosaic of spectral arrivals, rather than discrete echoes. This creates a more organic, evolving texture than conventional delay effects. The propagation characteristics can change based on input dynamics, with periods of abundance (sustained high signal levels) creating different behaviours than periods of scarcity (sustained low signal levels). During periods of abundance, network pathways may become saturated, creating back-pressure effects that slow further transport. Conversely, in times of scarcity, the gradient between haves and have-nots becomes more pronounced, potentially accelerating nutrient movement. This is a natural process in Sporadic, which can be overridden by the user with the dedicated "Scarcity/Abundance" panel control.

The rate of growth and the propensity to form associative structures are controllable by the "Growth Rate" and "Entanglement" knobs, respectively.

Network topology can, moreover, be modulated in real-time. For example, the "Stretch" control allowing the performer to manipulate the virtual space in non-linear and potentially destructive ways. The more stretch, the more distance between the trees, but also more fraying of the weaker connections. As the space gets compressed, connections are (re)formed by virtue of the colonies being pressed together in a confined space.

The "Fold" control has a different effect, as it is used to create foreground/background effects by scanning the network state spatially, similar to how a baker would differentially apply pressure while kneading dough. This allows performers to sculpt the spatial and temporal characteristics of the effect in ways that feel connected to natural processes rather than abstract parameters.

4.2.2.5 Understanding Mycelial Nutrient Distribution

Different fungal species have evolved remarkably distinct strategies for nutrient acquisition and distribution. This diversity of strategies reflects millions of years of evolutionary adaptation to varied ecological niches and substrate availabilities [32]. This complex topic can be viewed through the lens of inter- and intra-species differences, but also by understanding what occurs at the boundaries between different colonies.

Species-level specialisation. Different fungal species specialise in different nutrient acquisition strategies. Consider the ectomycorrhizal fungi (like many Basidiomycetes) that form symbiotic relationships with tree roots, primarily of woody plants. These organisms are masters at mobilising nitrogen and phosphorus from organic matter and soil minerals, creating microscopic trade routes that connect plant root systems with the broader soil ecosystem [38]. In contrast, arbuscular mycorrhizal fungi (such as Glomeromycota) specialise particularly in phosphorus uptake from the soil solution, developing intricate hyphal networks that allow plants to access nutrients far beyond the immediate reach of their root hairs [33] [41]. Other species, still, such as saprotrophic fungi, specialise in the breakdown of different organic compounds. Some species have developed the ability to break down lignin, the complex polymer that gives wood its structural integrity, while others excel at processing cellulose [32]. These specialised decomposers create localised nutrient release zones, effectively transforming dead biomass into available nutritional resources for the broader ecosystem.

Within-species specialisation. Imagine these fungal networks as living transportation systems. Even within a single mycelial colony, there can be functional specialisation. At the colony's growing edges, young mycelia are metabolically hyperactive, probing the environment and establishing initial nutrient corridors [35], [42] [43]. As these networks mature, they develop increasingly sophisticated enzymatic profiles, adapting to local substrate conditions and inter-species competition. The older sections of a mycelial network often transition from primary nutrient acquisition to become specialised transport infrastructure, efficiently moving resources to active growth fronts or reproductive structures [31] [36].

The movement of nutrients through mycelial networks involves a complex interplay of active transport and passive diffusion [36]. Specialised hyphae function like biological highways, with cytoplasmic streams moving resources bidirectionally at remarkable speeds. Local sensing mechanisms continuously detect resource imbalances, dynamically adjusting flow patterns to optimise nutrient distribution.

Some fungi, like *Phanerochaete velutina*, can transport nutrients over a metre or more through their cord systems, an extraordinary feat of biological engineering [36]. These networks create pressure gradients that drive mass flow, with specialised organelles involved in packaging and transporting nutrients across vast distances within the mycelium.

Competitive and Cooperative Interactions When different fungal colonies encounter one another, lively interactions emerge. These encounters are not simply passive meetings, but dynamic negotiations of territorial and nutritional boundaries. Some colonies form physical barrages, secreting inhibitory compounds to restrict neighbouring expansion, a phenomenon known as combat or interference competition [32]. These interactions create intricate mosaics of fungal domains, where each colony strategically manages its resource acquisition and potentially creates nutrition depletion zones to block encroachment by neighbours.

Yet, competition is not the only mode of interaction. In certain circumstances, genetically similar colonies can perform hyphal fusion, a process called anastomosis, where they the internal networks connect and resources are shared [33] [35]. This cooperative behaviour challenges simplistic notions of individual survival, revealing instead a more nuanced understanding of collaborative survival strategies and the potential for forming larger, more resilient collective individuals.

Perhaps most remarkable is the fungal ability to continuously remodel their networks. Less productive pathways may be abandoned through strategic hyphal death (apoptosis or autophagy) and retraction of cytoplasm, while high-throughput corridors are reinforced with additional branching structures or by thickening existing hyphae [31] [33] [35]. Mathematical analyses have revealed that these fungal networks often develop transport systems that rival human-designed infrastructure in their efficiency and resilience. A classic study [44] showed that the slime mold was able to reproduce the layout of the metropolitan Tokyo rail system in an experiment where nutrients were placed as proxies for dense urban areas on a map. While slime molds are not fungi, this highlights the capacity of decentralized biological networks to optimize transport pathways.

This continuous adaptation allows fungi to function as intelligent ecological agents. They are not merely passive decomposers or transporters, but active managers of nutrient landscapes, responding to environmental shifts, with a plasticity that challenges our traditional understanding of biological systems [32], [31]. The electrical signalling observed in fungi further supports this view of active information processing and response [45].

Musical Interpretation. These distribution dynamics translate into several key aspects of Sporadic's behaviour. Different colonies specialise in transporting different nutrients. Taking a prismatic approach to sound, different frequency bands will represent the nutrients, each with unique propagation characteristics, under the influence of the propensities of the different mycelial colonies. Multiple delay lines create the dispersive effect of redundant network pathways as well-trafficked mycelial connections are reinforced over time.

Where colonies intermingle, there will be competitive behaviour leading to barrages forming when the colonies are dissimilar, and potential for hyphal fusion when colonies' histories made them converge towards a similar tuning. Moreover, colonies can "attune" over time, with the effect becoming more responsive to regularly occurring spectral content. This directly translates into the widening and progressive re-centring of the spectral aperture of each colony as it ages. However, the growing edge of each colony will always be represented by younger hyphae with less refined palates.

Whenever the harmonic content changes (either due to a change of register or instrumental arrangement), there will be a period of adaptation and "retuning". This adaptation time creates a sort of "harmonic slack" in the system, where changes in musical elements generate transitional states rather than immediate responses. This plays into the concept of an *organismic behaviour*, where the effect develops a unique character based on how it is played. Sporadic is not simply a delay effect with fixed parameters. It is a dynamic system whose behaviour evolves over time in response to playing style. Just as a forest ecosystem develops unique characteristics based on its specific conditions and history, each instance of Sporadic develops its own sonic signature through use.

These underground networks are a profound reminder of nature's complexity. Fungi represent a form of distributed natural intelligence, decentralised, adaptive, and responsive. Their nutrient distribution strategies offer insights not only into ecological processes, but potentially into design principles for resilient, self-organizing systems.

The mycelial world teaches that survival is not about individual dominance, but about sophisticated cooperation, continuous adaptation, and nuanced resource management. In their silent, underground realm, fungi conduct an intricate symphony of life, one hyphal thread at a time.

4.2.3 Sporadic Topology Considerations

The analogies between biological reality and sound processing presented in Section 4.2.2 raise fundamental questions about how biomimetic delay systems should function at the signal processing level, particularly regarding the relationship between network topology and audio signal flow. The analysis of contemporary delay systems (Section 2.3.2) reveals a spectrum of approaches ranging from explicit network routing to implicit network-influenced processing, each with different implications for how biological principles might be implemented in audio processing systems.

Two primary architectural approaches emerge from this analysis, each offering different advantages and challenges to implement ecological principles in audio processing. The first approach involves literal network traversal, where audio signals are handled as they travel through a network of delay nodes, with the signal path determined by the current state of network connections. This approach envisions a series of delay lines with complex inner feedback loops created through the participation of neighbouring nodes in the network. In this model, the network topology directly determines the audio signal flow, creating a one-to-one correspondence between network structure and delay processing architecture.

This literal approach offers intuitive correspondence between the biological model and audio processing, making the system's behaviour more transparent to musicians. Filter bank analysis could determine how different frequency components of the input signal interact with various tree types, mimicking the dispersive propagation that occurs in natural acoustic environments. The challenge lies in managing the complexity of multiple simultaneous signal paths while maintaining audio quality and preventing unstable feedback conditions.

The alternative approach involves meta-interpretation, where the network evolution influences the configuration of traditional delay processing elements rather than directly routing audio signals. In this model, the network might control the parameters of all-pass filters, feedback matrices, or modulation routing without the audio signal necessarily traversing the network structure itself. This approach potentially offers more stability and predictability while still allowing network evolution to influence the sonic characteristics of delay processing. However, the relationship between ecological processes and sonic outcomes becomes less direct, potentially reducing the intuitive connection that makes biomimetic instruments compelling for both musical and educational purposes.

The choice between these approaches involves trade-offs between authenticity to biological principles and practical considerations of audio quality, computational efficiency, and musical usefulness. The literal approach offers more direct correspondence to biological function of the network, but may introduce stability challenges, while the meta-interpretive approach provides more control over audio processing characteristics while potentially losing some of the direct biological inspiration that motivates the system design.

These implementation considerations highlight the fundamental challenge of translating biological principles into audio processing systems: how to maintain the essential characteristics that make biological networks interesting and musically valuable while creating systems that function reliably and musically in practical applications. The examples provided by contemporary delay systems suggest that the most successful approaches will likely combine elements of both literal and meta-interpretive implementation, allowing biological principles to influence audio processing in ways that enhance musical expression while maintaining the stability and predictability necessary for practical musical use.

4.3 Third Quarter: Platform Choice

The third main implementation-specific decision is about the technological platform to use to deliver Sporadic in the hands of early users.

Before even diving into the specifics of various platforms, it is important to underline the fundamental essence of what the process of designing a musical instrument (or sound devices) really boils down to: sound design. Sound design transcends mere technical implementation, representing a deep dialogue between the creator, technology, and sonic potential. At its core, sonic expressivity emerges through the intricate relationship between an artist and their chosen platform of sound creation or manipulation. The effort of deciding on a platform has to support the goal of providing an appropriate level of musical expressivity to the artist.

Musical expressivity manifests itself through three interconnected domains: playability, interactivity, and compelling sound.

- **Playability** refers to the degree to which an instrument offers the dynamic levers and mechanisms that allow performers to shape sound in real-time. These are not merely control parameters, but intricate pathways of sonic exploration. A truly playable instrument provides complex routing possibilities, allows simultaneous modulation from multiple sources, and creates an environment where sound becomes a living, breathing entity that responds organically to the performer's intention.
- **Interactivity** is a connected concept that goes beyond the usage of a musical device during performance. The degree to which it invites physical engagement, translating manipulation of the user interface into intuitive musical intention. It encompasses the subtle responsiveness of touch-sensitive surfaces, the comprehensive overview and vast capabilities of computer-based graphical use interfaces (GUIs), the ergonomic design of controllers, and the immediate feedback mechanisms that translate physical gesture into sonic transformation.
- **Compelling sound**. Underlying these interactive dimensions lies compelling sound: the fundamental quality of sound before manipulation. This represents the platform's inherent capacity to generate rich, nuanced timbres, maintain dynamic range, and manifest a coherent sound design philosophy. It is the raw material from which sonic landscapes are constructed.

These aspects are some of the guiding lights for the remainder of this section, which is organised as follows: Section 4.3.1 outlines the possibilities considered for this project, while 4.3.2 zooms in on the chosen form, of a VST plugin. The latter section provides details regarding the tools, libraries and chosen architecture for Sporadic.

4.3.1 Platform Typology

The choice of form factor can be distilled to a high-level choice between hardware and software. Looking closer, there are more nuanced choices that mix aspects of both the hardware and software worlds.

4.3.1.1 High-level Platform Choice

At the high level, the first choice to make is between:

- **Hardware: The Tactile Realm**. Analog and modular systems represent a deeply physical approach to sound design. Their strength emerges from tangible interaction: patch cables that visibly route signals, knobs that provide immediate tactile feedback, and a signal path characterised by beautiful unpredictability. A Eurorack modular synthesiser is not merely an instrument, but a living ecosystem of sonic potential, where each module contributes to an ever-shifting landscape of sound.

  However, this physicality comes with inherent limitations. As an artist, the significant cost of entry and the substantial physical space required create barriers to exploration. Each module represents a financial and creative investment, making experimentation both exciting and potentially intimidating. As a developer, the added complexity of fabricating and debugging hardware is not to be discounted.

- **Software Platforms: The Digital Canvas**. Virtual Studio Technology (VST) platforms represent a fundamentally different paradigm. Here, sound becomes a computational construct, freed from physical constraints. An unlimited parameter space allows for complex sonic architectures that would be prohibitively expensive or impossible in hardware. Visualisation transforms sound from an auditory experience into a dynamic, explorable landscape.

  Yet, software platforms are not without compromise. The screen becomes both window and barrier, introducing a layer of abstraction that can distance the performer from immediate sonic interaction. The very flexibility of software can lead to decision paralysis: dozens of parameters presenting endless possibilities but potentially overwhelming creative focus.

4.3.1.2 The Modulation Imperative

Modulation represents the heartbeat of dynamic sound design, a concept that differs profoundly between hardware and software platforms. In modular hardware, modulation emerges through complex, often unpredictable, Control Voltage (CV) interactions. Signals flow and interact in ways that can surprise even experienced performers, creating organic, evolving soundscapes.

Software platforms often offer a contrasting approach: mathematically precise modulation with unlimited sources and perfectly reproducible modulation curves. Where hardware provides beautiful chaos, software delivers surgical precision. Neither approach is inherently superior; they represent different philosophical approaches to sound manipulation.

4.3.1.3 Design Considerations for Sporadic

Selecting a sound design platform transcends technical specifications. It involves understanding the proposed creative workflow, acknowledging the platform's learning curve, and recognising the sonic philosophy it encourages. The most compelling platforms are those that feel like natural extensions of creative intention, tools that inspire exploration rather than constrain imagination. Starting a new instrument design sits at the crossroads of possibility and must look beyond technical paradigms to find a hybrid approach that serves the design intent.

Contemporary sound design exists in a fluid landscape where technological boundaries blur. Creators now move fluidly between hardware prototyping, software development, embedded systems, and complex digital signal processing. The most exciting sonic territories emerge not from embracing a single platform, but from understanding the dialogue between different technological approaches.

4.3.2 Chosen Tech Stack

Given the overview in Section 4.3.1, and especially the conclusions drawn in 4.3.1.3, a hybrid approach is preferable, providing a mix of different solutions' strong points, while attempting to avoid their respective pitfalls.

Thus, for Sporadic, technologies chosen are a combination of a *hardware control surface*, with the interface mapped to MIDI Continuous Control (CC) messages controlling a *Virtual Studio Technology (VST) plugin*. This stack was chosen over many potential environments and tools for developing computer-based musical instruments, as summarised in Appendix A. This combination leverages the computing power and visualisation capabilities of the computer with the interactivity of tactile control. True to the belief that well-chosen constraints foster creativity, the GUI of the VST will be 1:1 mapped to the control surface control elements, for a true "knob per function" design. This serves a twofold benefit: on the one hand, the GUI remains focused on the instrument's essential controls, not overwhelming the user and leaving more space for the visualisation. On the other hand, the experience of using Sporadic with and without the controller will be similar (apart from the aforementioned tactile aspect).

To support the playability aspect mentioned at the beginning of this section, it is crucial for the success of this project that Sporadic responds to player input in a way that engages the musician to adapt and modulate their performance in dialogue with the instrument. Therefore, a critical aspect in the design of the instrument is to ensure a meaningful mappings between characteristics of the performance (*e.g.* playing dynamics) and the character of the sound design. This in line with the goals outlined in Section 1.2 and is conceptually orthogonal to the hardware vs software axis of discussion above.

The following subsections go over the various components used in the development of Sporadic.

4.3.2.1 JUCE: The Foundation of Cross-Platform Audio Development

In the early 2000s, audio software developers faced a significant challenge: creating applications that could run seamlessly across multiple platforms. Julian Storer, a British software engineer, recognized this need and created JUCE (Jules' Utility Class Extensions) in 2004, fundamentally transforming audio software development. JUCE emerged as a comprehensive framework designed to solve complex cross-platform development challenges. The core philosophy of JUCE revolves around three fundamental principles:

- **Platform Abstraction**. JUCE provides a unified API that abstracts away platform-specific complexities. For Windows, macOS, Linux, or mobile platforms, JUCE ensures consistent behaviour and minimal platform-specific code.
- **Modularity**. The framework is designed with extensive modularity, allowing developers to include only the components they need. This approach ensures lightweight applications and efficient resource management.
- **Real-Time Performance**. Audio software has relatively high demands on performance, and JUCE is engineered with real-time audio processing as a primary consideration. Its low-latency design makes it ideal for professional audio applications.

Moreover, JUCE has a number of key technical features which recommend it for VST development, such as cross-platform UI components with support for hardware-accelerated rendering, but also interfacing with system peripherals, such as various audio and MIDI devices. Moreover, it supports various plugin formats (depending on the target platform, among VST, AU, AAX, LV2 and, more recently, CLAP), as well as providing comprehensive threading utilities.

A very basic starting point for a JUCE plugin is shown below:

```
class MyAudioProcessor : public juce::AudioProcessor {
public:
  // Constructor and essential audio processing methods
  void processBlock(juce::AudioBuffer<float>& buffer,
                    juce::MidiBuffer& midiMsgs) override {
      // Real-time audio processing logic
  }
};

...
```

```
// This creates new instances of the plugin
juce::AudioProcessor *JUCE_CALLTYPE createPluginFilter()
{
  return new MyAudioProcessor();
}
```

4.3.2.2 Plugin-GUI-Magic: Rapid UI Prototyping

Plugin-GUI-Magic is a JUCE module that greatly simplifies audio plugin interface design. It transforms UI development from a purely programmatic task to a more designer-friendly, declarative approach, together with a "what you see is what you get" (WYSIWYG) editor.

Designers can define complex interfaces using XML, separating visual design from the underlying logic. The integrated design environment allows real-time UI composition without deep programming knowledge. Moreover, the responsive design concepts taken from web development (and fundamental HTML + CSS concepts) lead to facilitating responsive design, adapting interfaces to different screen sizes and resolutions.

An example of how an XML GUI definition looks like is shown below:

```
<magic>
  <Styles>
    <Style name="default">
      <Nodes/>
      <Classes>
        <group border="2" flex-direction="row" padding="1"/>
      </Classes>
      <Types>
        <Slider border="0"/>
        <ToggleButton border="0" max-height="50" caption-size="0"/>
        ...
  </Styles>
  <View id="root" flex-direction="column" resizable="1" [...]>
    <View border="2" background-colour="black" caption=[...]
          caption-size="0" title="Scope" pos-width="100%" [..]
          flex-align-self="center" display="contents" [...]>
          ...
  </View>
</magic>
```

4.3.2.3 Model-View-Controller (MVC) Architecture

The application has been designed from the ground up using a Model-View-Controller (MVC) Architecture, as shown in Figure 4.2.

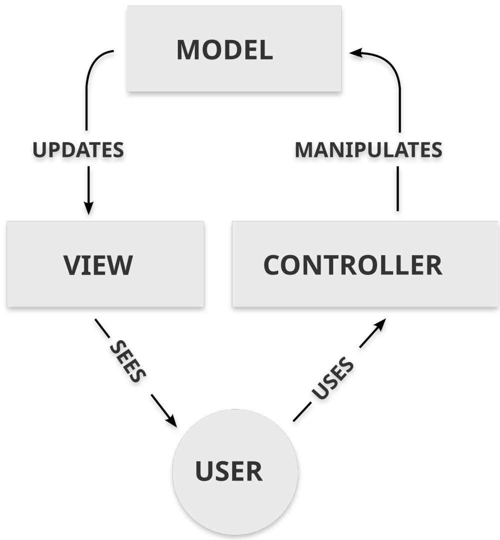

Figure 4.2: Model-View-Controller Architecture

MVC represents a fundamental design pattern that separates an application into three interconnected components:

- **Model**: Data and business logic
- **View**: Visual representation
- **Controller**: Intermediary managing interactions

There are a number of benefits to using an MVC architecture, amongst which improved code modularity, easier maintenance and testability are good reasons to consider it. In an interactive system such as a VST plugin, the clear separation of concerns between the interface and handling the state of the system is probably the primary argument for using this framework. The less that needs to be done in each context (potentially thread) in order to update a different part of the application, the more responsive the behaviour will be.

Below follows a very brief example of how the three main components in the MVC architecture would be defined in the plugin. Worth noting is that the controller acts as a bridge between the model and view in order to separate their concerns. In practice, this leads to a potentially high number of getter and setter functions that need to be exposed to the controller, leading to one of the main criticisms of this architecture.

```
class AudioPluginModel {
    // Represents underlying data and processing logic
    std::vector<ProcessingParameter> m_parameters;
```

```
};

class AudioPluginView {
    // Handles visual representation
    void updateParameterDisplay(const AudioPluginModel& model);
};

class AudioPluginController {
    // Manages interactions between model and view
    void handleUserInteraction(AudioPluginModel& model,
                               AudioPluginView& view);
};
```

4.3.2.4 Integrated Development Approach

Modern audio plugin development requires a sophisticated approach that combines robust frameworks, advanced visualisation techniques, and clean architectural patterns. By understanding and integrating well-chosen technologies, developers can create powerful, performant, and eye-catching audio applications. For Sporadic, the approach has been to:

- Use JUCE as the foundational framework
- Leverage Plugin-GUI-Magic for rapid UI prototyping
- Apply MVC architecture for robust design

4.4 New Moon: JUCE Implementation

Sporadic[2] has been developed as according to the principles outlined above. The next subsections outline the top level overview, including the user controls and MIDI CC message mappings (Section 4.4.1), the audio path implementation (Section 4.4.2), as well as information regarding the GUI implementation (Section 4.4.3).

4.4.1 Sporadic Top Level Overview

Sporadic follows a typical JUCE architecture with clear separation of concerns using the MVP pattern:

- Controller Class: `Mycelia` - Serves as the primary entry point
- DSP Model: `MyceliaModel` - Handles all audio processing and parameter management

[2]Github repository link

- View Components: Various view classes like `MyceliaView`, `NetworkGraphAnimation`, and `DuckLevelAnimation` handle UI rendering

The audio signal flows through these main stages:
`Input → Input Processing → EdgeTree → DelayNetwork → Output Mixing → Output (with a feedback path through the Sky block)`

The `MyceliaModel::process()` method coordinates this flow, with the `DelayNetwork` being the core effect component. The plugin uses Foleys GUI Magic for its UI framework, which provides a flexible XML-based layout system.

4.4.1.1 Functional Blocks

The following list summarizes the processing blocks in the design, together with the parameters controlling them (either via GUI elements such as knobs or via MIDI Control Change messages).

Input Sculpting. Handles initial audio conditioning through several components:

- **Preamp Gain** (CC#2). Controls input signal level.
- **Bandpass Filter** (CC#0, CC#1). Controls frequency content entering the delay network.
- **Reverb Mix** (CC#3). Controls amount of the reverb feedback loop. User control in the Output Sculpt block.

Tree Configuration. Controls the positions and properties of "trees" in the network:

- **Tree Size** (CC#4). Controls the envelope follower slope of the input tree and the reverb send of the remaining trees.
- **Tree Density** (CC#5). Controls density (thus number) of trees tapping into the network.

Delay Network. The core processor that creates the complex mycelial-like network of delays:

- **Diffusion Control** Splits the signal into multiple frequency bands.
- **Delay Nodes** A network of interconnected delay processors. Arranged in bands/colonies with complex routing.
- `nodeInterconnections` Controls how nodes are interconnected. Visual representation in the UI via `NetworkGraphAnimation`.

Universe Controls. Global parameters affecting the behaviour of the delay network:

- **Stretch** (CC#6). Controls the scale, and thus the timing in the delay network.
- **Scarcity/Abundance** (CC#7). Determines the gradients driving osmosis in the mycelial network. Can be automated or manually controlled.
- **Fold Position/Size/Shape** (CC#16, CC#17, CC#18). Allows the user to "fold" the network by temporarily scanning over the delay taps.

Mycelia Controls. Control the growth and behaviour of the delay network:

- **Entanglement** (CC#8). Controls interconnectedness of delay nodes.
- **Growth Rate** (CC#9). Controls how quickly the network evolves.

Sky Controls. Controls ambient reverb-like features, though a single macro-like knob in the Output Sculpting section:

- **Humidity** (CC#10). Controls the diffusion of the delay.
- **Height** (CC#11). Controls the pre-delay of the reverb loop.

Output Sculpting. Controls the final output mix:

- **Dry/Wet Mix** (CC#12). Controls blend between processed and unprocessed signal.
- **Height** (CC#11). Controls harmonic ducking of delay effect based on input level. Visualised through `DuckLevelAnimation`.

4.4.2 Sporadic Audio Path Implementation

The top-level diagram showing the logical organisation of Sporadic is shown in Figure 4.3. The plugin implements a delay network effect through a hierarchical architecture that separates concerns between audio processing, parameter management, and user interface components. The main entry point is the `Mycelia` class which serves as the primary JUCE plugin interface, handling all host communication, MIDI processing, and GUI management. This class delegates the actual audio processing to the `MyceliaModel` class, which acts as the central coordinator for all DSP operations and parameter state management. The model maintains references to all processing components and manages the complex signal routing between them, ensuring that parameter changes are propagated correctly throughout the entire processing chain.

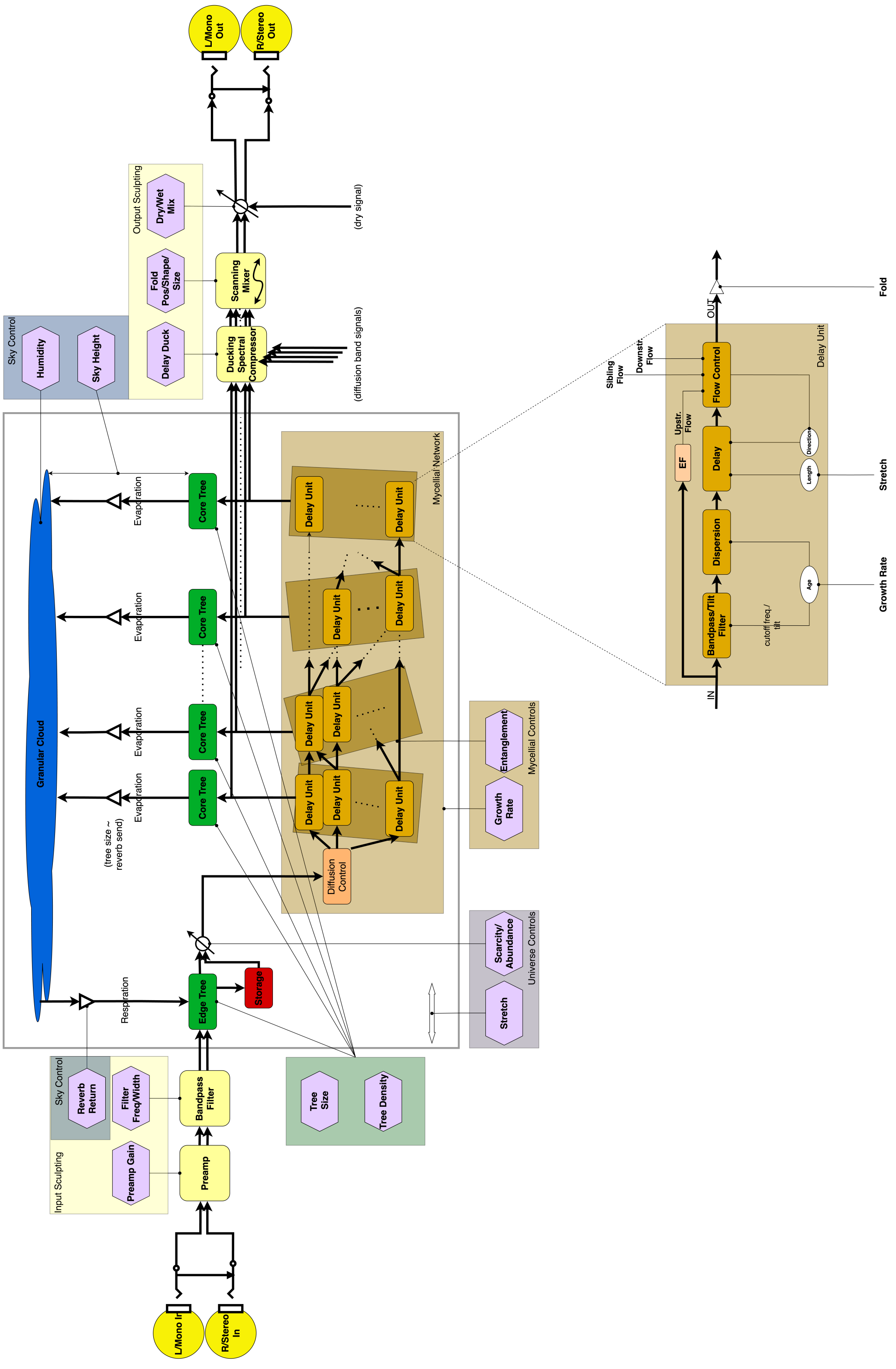

Figure 4.3: Sporadic Block Diagram

The `Mycelia` class implements comprehensive MIDI functionality including MIDI clock synchronisation for tempo-based delay timing and extensive MIDI CC mapping for real-time parameter control. The MIDI clock implementation calculates tempo from incoming clock messages and automatically adjusts delay times to maintain musical synchronisation with the host or external devices. The plugin maps 18 different MIDI CC numbers to various parameters, allowing for real-time control from external hardware controllers. The MIDI processing includes sophisticated timeout detection to handle cases where MIDI clock stops, and automatic parameter override detection that allows users to regain manual control after external automation.

Throughout the implementation, careful attention is paid to thread safety and real-time performance constraints. The audio processing components are designed to avoid memory allocation during processing and use lock-free communication mechanisms where possible to transfer data between the audio and GUI threads. The visualisation system operates on snapshot data that are captured atomically from the audio processing thread, ensuring that partially updated states never become visible to the user interface. Parameter changes are handled through atomic operations and careful ordering to ensure that the audio processing thread always sees consistent parameter states, even during rapid parameter automation or MIDI control scenarios. The plugin's timer-based update system ensures smooth GUI animation while maintaining strict separation between audio processing priorities and interface responsiveness.

4.4.2.1 Input Processing and Signal Conditioning

The signal processing chain begins with the `InputNode` class, which handles initial signal conditioning including preamp gain adjustment and bandpass filtering. This component uses a filtered waveshaper component to implement a configurable bandpass filter (with gain and saturation) that allows users to simultaneously focus the sound entering the delay network on specific frequency ranges, as well as add harmonics from the waveshaper saturation. It effectively acts as a frequency-dependent gate for the more complex processing that follows. The input node also manages reverb mixing parameters that influence how much of the reverberated signal gets routed back from the ambient `Sky` processor.

4.4.2.2 Edge Tree Processing and Envelope Following

Following input conditioning, the signal passes through the `EdgeTree` processor, which implements envelope-following functionality using the `EnvelopeFollower` component. The `EdgeTree` acts as a dynamic amplitude processor that responds to the input signal's envelope characteristics, scaling the signal based on its own amplitude content in a feedback-like manner. This creates a VCA effect that, depending on the tree size, manages transients and provides dynamic shaping that prepares the signal for the more complex delay network processing. The envelope follower itself uses configurable attack and release times with multiple level detection types including RMS and peak detection, allowing for precise control over how the processor responds to different types of audio material.

4.4.2.3 Delay Network Architecture and Band Processing

The core of the plugin's functionality resides in the `DelayNetwork` class, which orchestrates a complex multi-band delay processing system through several interconnected components. The network begins with the `DiffusionControl` processor, which splits the incoming audio into multiple frequency bands using a bank of tuned filters that create overlapping frequency regions. Each band represents a different aspect of the frequency spectrum, and the number of active bands can be controlled to balance processing complexity against audio quality. The diffusion control maintains separate buffers for each frequency band and uses sophisticated filter design techniques to ensure minimal phase distortion and smooth transitions between adjacent bands.

DelayNodes - Multi-Dimensional Processing Matrix. The heart of the `DelayNetwork` class lies in the `DelayNodes` class, which implements a complex matrix of delay processors arranged in both frequency (mycelial colonies) and temporal nodes (tree root taps). The `DelayNodes` class manages the complex interconnection topology between these processors, implementing dynamic routing algorithms that allow delay nodes to feed into each other based on parameters like entanglement and growth rate. The growth rate of the network influences the metabolic age(*i.e.* increments only in the presence of audio signal) of the delay nodes.

Delay Processors Each delay node within this matrix contains an instance of the `DelayProc` class, which provides individual delay lines with configurable delay times, feedback amounts, and internal processing characteristics. The `DelayProc` processing chain begins with a tilt filter centred on the band frequency. The tilt is modulated by an LFO with randomized start phase. The LFO frequency starts from the current tempo (and linearly decays to 0 with age). The tilt modulation depth is 6dB. This simulates the "tuning" phase of earlier stages of colony life. The `DelayProc` delay time is set according to the master tempo (+ a probable variation for "swing"), with a multiplication/division factor offered by the stretch. This translates into the quickest time for a full aging cycle being equal to 100 quarter notes (25 bars). With extremely low growth rates, this will grow to 25000 bars, for a geological-scale evolution. As the node ages, it becomes better at transporting nutrients by reinforcement of its "high value" links with parallel thread. This leads to the phenomena of dispersion, which is implemented in the `DelayProc` class according to the paper in[46]. The implementation here uses up 10 all-pass stages, with the number controlled by the age level. The aging process itself is based on the These features, in conjunction, create emergent behaviour, where the delay network can evolve and change its characteristics over time, mimicking the growth patterns of biological systems.

Tree Connection System and Input Distribution The `DelayNodes` implementation includes a tree connection system that determines how the input signal is distributed from the various delay processors (and frequency band) to the output. The tree positions are calculated dynamically based on the tree density parameter (in Euclidean fashion, with allowance for variance providing natural "swing", and these positions determine which delay nodes provide access to the processed signal at the tree level). This system allows for complex input routing scenarios where different delay nodes can be "tapped" or "untapped" based on the current parameter settings. This creates the visual metaphor of trees growing and connecting to different parts of the delay network. The connections are visualized in real-time through the `NetworkGraphAnimation` component, providing users with immediate feedback about how their parameter changes affect the internal signal routing.

Inter-Node Communication and Network Topology One of the most sophisticated aspects of the DelayNodes implementation is its inter-node connection system, which creates complex feedback networks between individual delay processors. The strength of these connections is controlled by the entanglement parameter, which determines the probability of creating a connection (as well as setting a ceiling to how much signal flows between connected delay nodes upon connection). The connection topology is maintained in multi-dimensional arrays that store connection weights between all delay processors. The growth rate parameter influences how these connections evolve over time, with higher growth rates leading to more rapid changes in the network topology and lower rates creating more stable, slowly evolving soundscapes. Depending on the tempo, as often as 4 measures (16 beats), the connections are updated. The growth rate acts as a frequency divider of the update rate, allowing for a glacial pace of updating (all the way to turning off the updates entirely). The entanglement parameter, as well as the distance between nodes (with nodes on different bands weighted as being further apart), influence the probability of *new* connections being formed. For existing inter-node connections, the strength of the connection is updated with a delta depending on the entanglement rate and the age of the nodes. With ages below 50%, the delta is positive, while ages above 50% lead to decreasing the connection strength. The sum of all outgoing connections from a particular node is normalized to 100% in order to ensure that runaway feedback cannot occur.

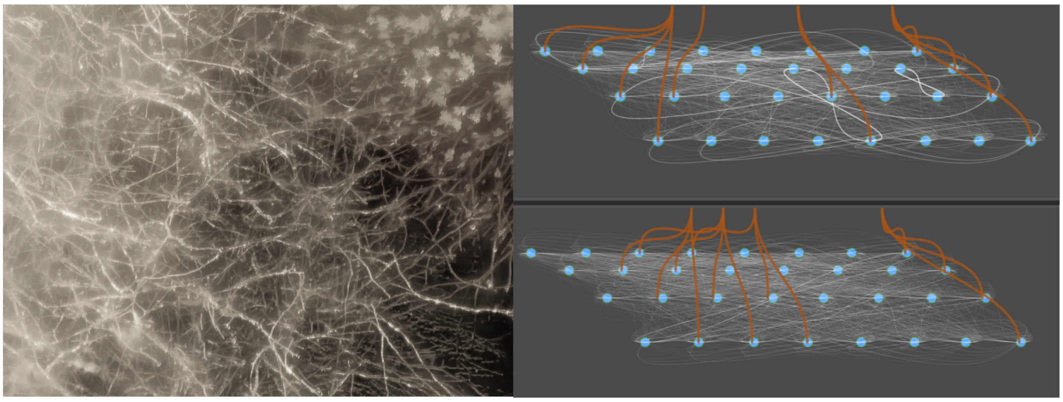

Figure 4.4: Mycelia Growth Patterns. Left: Still from Fantastic Fungi[47]. Right: The node interconnections taken from two different sessions of Sporadic.

4.4.2.4 Output Sculpting

The final stage of processing is handled by the `OutputNode` class, which combines the various processed signals and applies final level adjustments and ducking compression. The output node receives both the dry signal (post-input conditioning) and the wet signal (post-delay network processing), along with the individual band buffers from both the diffusion and delay stages. This allows for sophisticated mixing algorithms that can balance the various components based on their frequency content and dynamic characteristics.

Fold Window Processing and Temporal Manipulation The `OutputNode` class implements a unique fold window system that allows for non-linear manipulation of the delay network's temporal characteristics. The fold window is defined by three key parameters: position, shape, and size, which together create a dynamic window that moves can be moved the delay network and applies varying amounts of gain for mixing temporal regions. This system allows users to zoom in on complex rhythmic variations and temporal distortions that are not typical of delay processors. The fold window calculations ensure smooth transitions and prevent audible artifacts while maintaining the musical coherence of the processed audio.

Ducking Compression Each delay band includes a spectral ducking compression functionality implemented through the `DuckingCompressor` class, which provides sidechain-style compression where the diffusion bands act as control signals for their corresponding delay bands. This creates a responsive system where the presence of audio content in specific frequency ranges can dynamically control the level of audible delay processed signal in those same ranges. The ducking compressor implements standard compression parameters including threshold, ratio, attack, and release times, but applies them in the context of spectral processing where the detection circuit and the gain reduction circuit operate on a specific frequency bands. This approach allows for extremely musical ducking effects that respond naturally to the frequency content of the input signal.

4.4.2.5 Sky Processing and Ambient Generation

Parallel to the main delay network processing, the plugin includes a `Sky` processor that generates ambient textures and atmospheric effects. The `Sky` processor operates on the delay-processed signal and applies a reverb algorithm with parameters for diffusion and pre-delay. The humidity parameter affects the density and character of the reflections, while the height parameter controls the pre-delay and decay behaviour. The Sky processor's output is mixed back into the main signal chain at the input stage, providing a layer of spatial feedback that complements the rhythmic and temporal effects of the delay network. This mirrors the evaporation and respiration into the shared air surrounding the trees, doubling as a means of recirculating energy and matter on a separate path compared to the mycelia network.

4.4.3 GUI Design

Sporadic integrates with the Foleys GUI Magic framework to provide a flexible, XML-based user interface system that allows for complex layouts and custom component integration. The `MyceliaView` components demonstrate the framework's capabilities through custom animation elements that respond to parameter changes and provide visual feedback. Each custom component is wrapped in a corresponding `ViewItem` class that handles the integration with the GUI Magic system, including property configuration, update notifications, and colour scheme management. The GUI system maintains bidirectional communication with the audio processing components, ensuring that visual representations accurately reflect the current processing state while allowing user interactions to immediately affect the audio processing parameters.

A view of the GUI and the offered controls is shown in 4.5.

The GUI contains three main elements, detailed in the next subsections.

4.4.3.1 Upper Panel with I/O and Performance Controls

The upper panel spans the entire width of the interface and is divided into three distinct functional sections:

Input Sculpt (Left) A golden-yellow section featuring a "Preamp Gain" knob. Beside the knob is a real-time spectrum analyser overlaid with an XY pad that

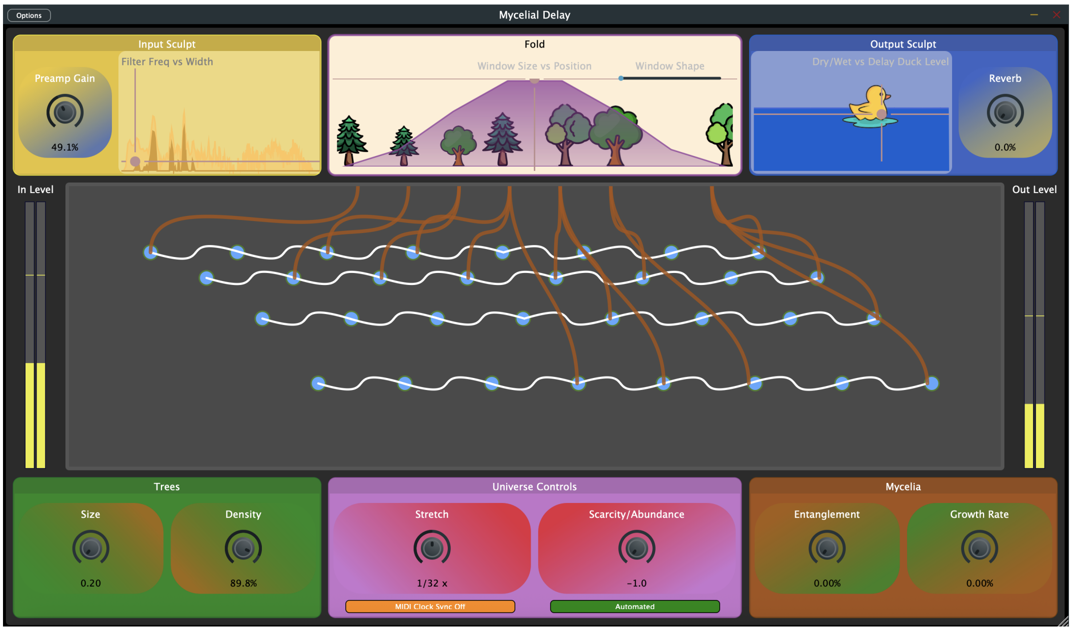

Figure 4.5: GUI Layout

controls the input bandpass filter frequency vs its width. The spectrum analyser displays the frequency content of the input signal in orange with the processed dry signal in a darker shade. This visualisation directly reflects how the bandpass filter affects the incoming signal, providing immediate visual feedback for frequency-based input conditioning.

Fold (Center) A lavender-purple section that controls the temporal manipulation aspects of the delay network. It features an XY pad for the "Window Size vs Position" parameter and a slider for the "Window Shape" parameter, with a distinctive graphical representation showing the fold window positioned above the tree icons representing the current distributions of trees in the environment. This visualisation represents how the fold window is currently interacting with different elements of the delay network, with the position and shape of the purple overlay directly corresponding to the actively observed region.

Output Sculpt (Right) A blue section featuring a "Dry/Wet vs Delay Duck Level" display with an animated yellow rubber duck floating on a water line, visually representing the current balance between dry and processed signal along with the ducking amount. The vertical position of the duck corresponds to the current dry/wet balance, while its horizontal position represents the ducking threshold. To the right is a "Reverb" knob, acting as a macro that controls the final reverb mix amount in the input stage, as well as the diffusion (sky humidity) and pre-delay and decay amounts (sky height).

4.4.3.2 Visualisation System and Real-Time Feedback

Sporadic's visualisation system provides multiple real-time graphical representations of the internal processing state through several custom animation components. The `NetworkGraphAnimation` class creates a visual representation of the delay network topology, showing individual delay nodes as coloured circles with connections between them represented as curved lines. The visualisation system receives snapshot data from the delay network and translates it into spatial coordinates using algorithms that map delay times to horizontal positions and frequency bands to vertical positions.

Moreover, the snapshot information includes relevant information such as buffer levels for individual delay nodes, inter-node connection weights, delay times, and tree connection states. The component also tracks external parameters like stretch factor, number of active bands, and tree positions, which directly influence both the audio processing and the visual representation. The stretch parameter fundamentally alters the spatial distribution by modifying the effective canvas width used for node placement, creating the visual effect of the network expanding or contracting horizontally while maintaining proportional relationships between delay nodes.

Individual delay nodes are rendered as circular elements with dual-colour encoding that conveys multiple pieces of state information simultaneously. The node's fill colour represents the age or accumulated processing time. The border colour encoding provides real-time feedback on buffer activity levels, with colours smoothly transitioning from low-level to high-level indicators based on the current signal amplitude passing through each delay node. The visual feedback system ensures that users can immediately perceive which parts of the delay network are actively processing audio and how intensively they are being utilised.

The animation system uses cubic Bezier paths to create organic-looking connections that reinforce the biological metaphor of the plugin's design. Connection weights determine both the visual prominence and colour characteristics of these pathways, with higher weights resulting in thicker lines and more saturated colours. The path generation algorithm calculates control points dynamically based on the spatial relationship between connected nodes, creating different curve characteristics for horizontal connections within the same frequency band versus vertical connections between different bands. This approach ensures that connection paths never appear harsh or mechanical, instead flowing naturally across the canvas in ways that suggest biological growth patterns.

The tree connection rendering system creates vertical pathways from the top of the canvas down to specific delay nodes, visually representing the input signal's entry points into the delay network. These connections use a semi-transparent amber colour scheme that distinguishes them from inter-node connections while maintaining visual coherence with the overall design. The positioning algorithm for tree connection points at the top of the canvas takes into account the stretch parameter and applies consistent spacing calculations that ensure alignment with other UI elements. The curved paths from top connection points to delay nodes use carefully calculated control points that create natural-looking arcs, avoiding visual conflicts with the dense network of inter-node connections below.

Both sides of the interface feature vertical level meters showing input levels on the left and output levels on the right, providing immediate visual feedback on signal strength throughout the processing chain.

4.4.3.3 Lower Panel with Simulation Parameters

The lower panel contains three control sections that govern the core algorithmic behaviour of the plugin:

Trees (Left) - A green section featuring two knobs: "Size" and "Density". These parameters control the size and density of the trees, directly affecting how many taps exist and how prominent their contribution is to the energy storage is on the overall sound.

Universe Controls (Center) - A purple section containing two primary knobs: "Stretch" and "Scarcity/Abundance". Below these are two indicator labels: an "MIDI Clock Sync Off/On" indicator (for the MIDI clock sync state) and an "Automated/Overridden" indicator (for the state of the scarcity/abundance override. This section controls global timing relationships and nutrient saturation aspects of the delay network. The stretch parameter determines the temporal scaling of the model, with values left of noon quantized to musical meter divisions from the MIDI clock rate (or the default 120 BPM in its absence), while the right of noon values are continuous (relative to the same master clock). The scarcity/abundance indicator reflects resource distribution throughout the network when the value is automated and functions as a global override whenever the knob is moved (or MIDI CC7 is received).

Mycelia (Right) - An orange-brown section with two knobs labelled "Entanglement" and "Growth Rate". These parameters control the core behavioural characteristics of the mycelial network - how interconnected the delay nodes become and how quickly their relationships evolve over time. These parameters directly influence the complexity and temporal evolution of the delay effect, allowing for sounds ranging from static, predictable patterns to complex, ever-changing textures.

Chapter 5

Evaluation

Let Them Eat Tape

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5.1 Introduction

The evaluation of Sporadic was conducted through a user study involving eight participants with varying levels of musical experience. This chapter presents a comprehensive analysis of how well the project achieved its stated objectives, as well as the reseach goals outlined at the beginning of this report (Section 1.2). The evaluation draws upon both quantitative survey data and qualitative user feedback to assess the effectiveness of the biomimetic approach in creating a meaningful musical instrument.

The participant pool represented a diverse range of musical backgrounds, with 25% having less than two years of experience, 25% having 2-5 years, 12.5% having 5-10 years, and 37.5% having more than ten years of musical experience. This distribution provided valuable insights into how the instrument performed across different levels of musical expertise and familiarity with audio processing tools.

5.2 Experimental Design and Methodology

5.2.1 Evaluation Framework Considerations

The evaluation of digital audio effects and novel musical interfaces presents unique methodological challenges, as there are no widely established frameworks specifically designed for assessing VST plugins. Traditional software usability testing focuses primarily on task completion and efficiency metrics, such as the System Usability Scale (SUS). Such approaches, despite their merit, are insufficient for evaluating creative tools where the goal is exploration, expression, and aesthetic engagement rather than specific task achievement.

This evaluation drew inspiration from NIME (New Interfaces for Musical Expression) evaluation methodologies, particularly the framework outlined by Schmid [48], which emphasizes the multi-dimensional nature of musical interface assessment. Schmid's approach recognizes that musical interfaces must be evaluated across technical, experiential, and conceptual dimensions, considering not only functional performance but also the quality of creative engagement and the meaningfulness of the interaction paradigm.

However, Sporadic's nature as a VST required adaptations to existing NIME evaluation approaches. Unlike physical controllers or gestural interfaces that are typically the focus of NIME research, Sporadic functions as both a traditional audio effect and a conceptual exploration tool. This dual nature necessitated an evaluation approach that could assess both its utility as a music production tool and its effectiveness as a medium for ecological education and creative discovery.

5.2.2 Experimental Protocol

The evaluation employed an unmoderated exploration-based methodology designed to assess three primary dimensions identified as crucial for biomimetic instrument evaluation: sound quality, quality of interaction, and conceptual integrity. This approach was chosen to allow participants to engage with Sporadic in a naturalistic manner, reflecting how musicians typically encounter and explore new audio processing tools.

Each evaluation session followed a standardized protocol:

Introduction Phase (5 minutes) Participants received a brief introduction to the forest ecosystem concept underlying Sporadic's design. This introduction covered the basic principles of mycelial networks, nutrient exchange, and forest interconnectedness without providing detailed technical explanations of the parameter mappings. The goal was to establish conceptual context while preserving the exploratory nature of the evaluation.

Interface Orientation (5 minutes) Participants were given an overview of the available controls and their ecological inspirations. This included identification of major interface sections (tree controls, mycelial networks, environmental parameters) and basic interaction methods, but deliberately avoided detailed explanations of parameter behaviours to encourage discovery-based interaction.

Free Exploration Phase (15-20 minutes) The core evaluation period allowed participants to explore Sporadic's capabilities without specific tasks or goals. Participants were encouraged to experiment with different audio inputs, parameter combinations, and interaction approaches. This unstructured exploration was designed to reveal the instrument's capacity to encourage curiosity and reward experimentation, key objectives identified in the project goals. The experimental setup (shown in Figure 5.1) consisted of a laptop running the VST, a looper/sampler app running on the phone for selecting sounds to process, as well as two hardware controllers, shown in Figure 5.2.

The Expressive-E touché allows for simultaneous 4-axis expressive control, and was mapped to 3 controls of the fold window as follows:

- pressing the lower "lip" of the control surface was mapped to the unipolar *fold window size* parameter
- pressing the upper "lip" of the control surface was mapped to the unipolar *fold window shape* parameter
- moving the control surface to the sides was mapped to the bipolar *fold window position* parameter

.

The KORG nanoKONTROL Studio had six rotary knobs mapped to the remaining controls on the upper side of the interface (three for input sculpting, three for output sculpting, respectively). Six of the faders on the lower side of the controller were mapped to the six controls on lower side of the GUI (controlling Tree and Mycelia parameters, as well as the Universe controls).

Figure 5.1: Evaluation Setup

Figure 5.2: Hardware Controllers Used in the Evaluation. From the left: KORG nanoKONTROL Studio[49], Expressive-E touché[50]

Reflection and Survey (10 minutes) Immediately following the exploration phase, participants completed a comprehensive survey designed to capture their experience across multiple dimensions. The survey included both quantitative Likert-scale questions and open-ended qualitative prompts to gather detailed feedback on their interaction experience.

5.2.3 Evaluation Dimensions and Metrics

The evaluation framework focused on three interconnected dimensions that reflect the unique challenges of biomimetic instrument design:

- **Sound Quality Assessment**: This dimension evaluated Sporadic's effectiveness as an audio processing tool, measuring the perceived quality and musical utility of the sonic transformations it produces. Metrics included ratings of sound quality, expressive manipulation capability, and suitability for different musical contexts.
- **Interaction Quality Evaluation**: This dimension assessed the effectiveness of the ecological metaphors in creating intuitive and engaging interaction experiences. Metrics included control intuitiveness, system responsiveness, and the balance between user agency and system autonomy. Particular attention was paid to users' experiences of "collaborating" with the system rather than simply controlling it.
- **Conceptual Integrity Assessment**: This dimension evaluated how well Sporadic communicated its underlying ecological concepts and fostered understanding of forest ecosystem dynamics. Metrics included conceptual clarity, educational effectiveness, and the alignment between ecological inspiration and musical implementation.

Quantitative measures used 7-point Likert scales to assess various aspects of the system, while open-ended questions encouraged detailed descriptions of the interaction experience, most engaging controls, and suggestions for improvement. Questions were designed to assess not only functional effectiveness but also emotional engagement, conceptual understanding, and creative inspiration. These are factors that are crucial for evaluating tools intended to foster exploration and wonder.

This methodological approach provided a comprehensive foundation for assessing Sporadic's effectiveness across its multiple objectives while acknowledging the unique challenges inherent in evaluating biomimetic musical instruments that serve simultaneously as creative tools, educational resources, and conceptual explorations.

5.2.4 Methodological Considerations and Limitations

The unmoderated approach was chosen to maximise ecological validity, allowing participants to engage with Sporadic in a manner similar to how they might encounter it in real-world creative contexts. However, this approach also introduced limitations in data collection, interaction patterns were not recorded in real-time or probe specific moments of confusion or discovery.

The 15-20 minute exploration period represented a compromise between providing sufficient time for meaningful engagement while maintaining participant attention and preventing fatigue. This duration aligned with typical initial encounters with new audio processing tools, though it was not intended not capture longer-term learning and adaptation processes that are crucial for complex biomimetic systems.

The participant pool size (n=8) was appropriate for qualitative evaluation of novel creative tools, allowing for rich feedback while remaining manageable for detailed analysis. The diversity in musical experience levels provided valuable insight into how the biomimetic approach functions across different levels of domain expertise, from novice to expert musicians. Future evaluations would focus on three main directions:

- Expand to a more statistically-significant pool of participants
- Longitudinal studies with periodic user interviews
- A task-based study with probes after each task is completed

5.3 Assessment Against Project Objectives

5.3.1 Functional Prototype Development

The primary objective of creating a functional prototype of a forest-inspired audio processor was successfully achieved. Users consistently categorised Sporadic as a multifaceted effect, with 87.5% identifying it as a texturiser, 75% as a reverb, and 50% each as a delay and micro-looper. This multicategory classification suggests that the biomimetic approach successfully created an audio processor that transcends traditional effect boundaries, embodying the complex, interconnected nature of forest ecosystems.

The prototype demonstrated robust functionality across different use cases, with 87.5% of users finding it applicable as a sound design tool and 75% seeing potential for live performance applications. This versatility indicates that the forest-inspired design philosophy successfully translated into practical musical utility while maintaining conceptual integrity.

5.3.2 Ecological-to-Audio Parameter Mapping Framework

The establishment of meaningful relationships between ecological concepts and audio processing parameters showed mixed results. Users rated the quality of the controls, mappings, and intuitiveness at 4.75 out of 7, indicating moderate success but room for improvement. User feedback revealed that while some parameter mappings were intuitive and engaging, others proved difficult to understand or perceive aurally.

How would you rate the quality of the following aspects of Sporadic:

Statement	Extremely poor	Very poor	Poor	Moderate	Good	Very good	Exceptional	Overall
Controls (mappings, intuitiveness, explanation)	0 0%	0 0%	0 0%	4 50%	2 25%	2 25%	0 0%	8 n = 8
Expressive manipulation	0 0%	0 0%	1 12.5%	2 25%	4 50%	0 0%	1 12.5%	8 n = 8
Quality of sounds achievable	0 0%	0 0%	0 0%	2 25%	1 12.5%	5 62.5%	0 0%	8 n = 8
Rewarding curiosity and exploration	0 0%	0 0%	0 0%	1 12.5%	4 50%	0 0%	3 37.5%	8 n = 8

Figure 5.3: Survey Results Related to Quality

Participants found certain controls particularly engaging, with the stretch and density parameters receiving specific praise for their expressive potential. One user noted that "the combination of stretch and density was really cool, and I could see myself heavily modulating/automating it in my normal setup." However, other mappings, such as the fold parameter, were described as "tricky to use in a causal way," suggesting that some ecological metaphors may need refinement to achieve optimal musical expression.

The temporal scaling challenge, identified as a key research problem, appears to have been only partially addressed. Users appreciated the dynamic nature of the system, though some noted difficulty in understanding when changes were occurring due to long delay lengths and system complexity. Here, refining the visualisation further to make different ranges of parameters clearer to evaluate appears to be the logical means of addressing this. This is similar to other reflections regarding the design of the interface in the next paragraph.

5.3.3 Interface Design and Ecological Communication

The interface successfully communicated ecological concepts to users. Participants rated how well Sporadic matched the forest ecosystem concept at 6.12 out of 7. Moreover, the VST was notably rated as "exceptionally" novel conceptually by 37.5% of users, with no participants rating it below "very much" in this category.

In terms of concept communication, users particularly appreciated visual elements such as the duck visualisation for ducking effects and the root system displays that reflected "cross-contamination between audio streams".

However, the evaluation revealed a critical gap in educational communication. The most frequently cited improvement was the need for explanatory elements, with one user suggesting "inputting little caption-style explainers for the user to

Please answer the following questions:

Statement	Not at all	Very little	Little	Moderate	Some	Very much	Exceptionally	Overall
How well did you find Sporadic matched the forest ecosystem concept?	0 0%	0 0%	0 0%	0 0%	2 25%	3 37.5%	3 37.5%	8 n = 8
To what degree did you enjoy "collaborating" with an entity you can influence but not fully control?	0 0%	0 0%	0 0%	3 37.5%	1 12.5%	2 25%	2 25%	8 n = 8
To what degree did a sense of boredom/lack of variation set in during the session?	1 12.5%	3 37.5%	3 37.5%	0 0%	1 12.5%	0 0%	0 0%	8 n = 8

Figure 5.4: Conceptual Revelance, Ecological Collaboration and Boredom

click on to learn or remind themselves of the functions of nature, the musical metaphors, and mappings." This feedback indicates that while the interface successfully embodied ecological concepts, it could better serve its educational objective through more explicit explanatory features.

5.3.4 Encouraging Creative Exploration

The objective of fostering exploratory creative engagement was notably successful. Users rated the system's ability to reward curiosity and exploration at 5.62 out of 7, with many participants reporting extended engagement periods. One user specifically noted: "I lost track of time and my mind relaxed, totally engaged," while another observed that "this kept my attention for much longer than I would play with most other VSTs."

To what degree this evaluation session elicited feelings of:

Statement	None at all	Very little	Little	Moderate	Some	Very much	Exceptionally	Overall
Curiosity	0 0%	0 0%	0 0%	0 0%	0 0%	5 62.5%	3 37.5%	8 n = 8
Frustration	0 0%	3 37.5%	1 12.5%	2 25%	2 25%	0 0%	0 0%	8 n = 8
Excitement	0 0%	0 0%	0 0%	3 37.5%	2 25%	1 12.5%	2 25%	8 n = 8
Boredom	4 50%	2 25%	1 12.5%	1 12.5%	0 0%	0 0%	0 0%	8 n = 8

Figure 5.5: Survey Results Related to Emotional Engagement

The balance between autonomous system behaviour and user control proved at least moderately effective, with users rating their enjoyment of "collaborating" with an entity they could influence but not fully control at 5.38 out of 7. This suggests that the system successfully achieved the delicate balance between predictability and surprise that was identified as a key research challenge. However, 3 of the 8 participants had a moderate response to this question, hinting at the need to better manage the users' expectations regarding the type of interaction to expect from the VST.

Significantly, users reported very high levels of curiosity (6.38 out of 7) and moderate excitement (5.25 out of 7) while experiencing minimal boredom (1.88 out of 7). The moderate excitement can be at least partially explained by the issues with lack of more visibility indicated by some users. These emotional engagement metrics strongly support the achievement of this objective.

5.3.5 Effectiveness in Musical Contexts

The biomimetic approach demonstrated clear effectiveness in musical contexts, with users rating the sound quality achievable a solid 5.38 out of 7. However, expressive manipulation capabilities were rated only 4.75 out of 7, showing clear room for improvement. This is closely aligned to the relatively low score in the "Intuitive to play" category. The system was particularly successful as a sound design tool, with 87.5% of users identifying this as a primary application.

To what degree would you rate Sporadic as being:

Statement	None at all	Very little	Little	Moderate	Some	Very much	Exceptionally	Overall
Intuitive to play	0 0%	0 0%	2 25%	2 25%	3 37.5%	0 0%	1 12.5%	8 n = 8
Novel conceptually	0 0%	0 0%	0 0%	0 0%	0 0%	5 62.5%	3 37.5%	8 n = 8
Appealing sound-wise	0 0%	0 0%	1 12.5%	1 12.5%	0 0%	5 62.5%	1 12.5%	8 n = 8

Figure 5.6: Sporadic Attributes

However, the evaluation also revealed some limitations in immediate musical utility. Users noted that the system could be "quite easy to set to configuration in which it would not produce any sound," indicating that the complexity of the biomimetic approach sometimes hindered rather than helped musical expression. This finding highlights the ongoing tension between conceptual integrity and practical usability.

Sample selection also emerged as important considerations, with users noting that not all provided audio materials worked well with the system's processing approach. This finding suggests that Sporadic may benefit from careful curation of compatible input materials or tuning that will broaden the appeal of the way it responds to different types of audio content.

5.3.6 Human-Nature-Technology Relationships

The project successfully contributed to broader dialogues about human-nature-technology relationships. Users consistently recognised the ecological inspiration, with several noting the educational potential of the system. One participant suggested it would work well as "an interactive science museum piece," while another appreciated how it helped visualise "something that is so difficult to visualise and considering the fact that some people may not even know how forest work underground". Users demonstrated clear understanding of the forest ecosystem metaphor, rating conceptual matching at 6.12 out of 7.

The system's ability to transform users' thinking about technology and nature was evident in qualitative feedback, with participants describing the experience as going "beyond being a VST" and feeling "more like a game than it does a (*editor's note:* musical) tool." This suggests successful achievement of the objective to position technological creation as informed by and respectful of natural processes.

However, the educational impact could be strengthened through more explicit pedagogical features. Users requested better explanations of the ecological processes and their musical mappings, suggesting that while the system successfully engaged users with ecological concepts, it could more effectively deepen their understanding of forest ecosystem dynamics.

5.3.7 Final Thoughts on Evaluation Results

Through the evaluation process, several key design principles for biomimetic instruments emerged. The feedback suggests that successful biomimetic design requires careful attention to the relationship between conceptual complexity and user accessibility. Users appreciated sophisticated ecological metaphors but needed better support for understanding these relationships. This reflects the broader challenge of balancing conceptual communication with practical usability in interface design.

The principle of "familiar entry points with esoteric depth" emerged from user behaviour, with one participant noting: "I started playing with frequency and reverb controls, things that a musician knows best. Then as time went on I became more interested in exploring the more complex, many-to-many mapping parameters such as tree growth, abundance, and the more conceptually complex parameters.". This holds promise for rewarding users' longer-term commitment to experimenting with Sporadic.

Chapter 6

Conclusions and Future Work

Push the Sky Away

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The evaluation of Sporadic (detailed in Section 5) demonstrates that biomimetic approaches to instrument design represent a viable and valuable direction for the development of expressive musical technologies. The project successfully achieved its primary objectives of creating a functional forest-inspired audio processor that encourages creative exploration while educating users about ecological processes. The system's ability to engage users in extended creative sessions while maintaining conceptual integrity validates the core premise that natural systems can serve as meaningful sources of inspiration for musical interface design.

> " *Complex systems are always adapting to changes in their component parts, and the world around them.*
> *This means that we need to maintain relationships with them, constantly learning and improving our interventions, as they change.*
> *So, working with a system, with a full appreciation of its dynamics, allows us to steer it towards more sustainable paths in which its momentum is naturally aligned with our desired outcomes.*"
>
> - Alex Penn

The most significant success was the system's ability to engage users in extended creative exploration while maintaining conceptual integrity. Users consistently recognised and appreciated the ecological inspiration, finding the system both novel and musically useful. The balance between autonomous system behaviour and user control proved particularly effective in creating a collaborative relationship between musician and instrument.

However, the evaluation also revealed important challenges in biomimetic design. The complexity inherent in ecological systems can create barriers to immediate musical utility, requiring careful design decisions about when and how to abstract or simplify natural processes. The need for better explanatory features and clearer parameter mappings suggests that successful biomimetic instruments require sophisticated educational scaffolding to help users understand and use the VST effectively.

Looking forward, the evaluation suggests that biomimetic instrument design benefits from an iterative approach that continuously refines the balance between conceptual inspiration and practical implementation. The most successful aspects of Sporadic were those that provided clear connections between ecological concepts and musical outcomes, while the less successful aspects were those where this connection remained opaque or overly complex.

The project's contribution to broader dialogues about the human-nature-technology relationships is successful, with users recognising the educational and philosophical implications of biomimmicry. This suggests that such projects can indeed serve as bridges between technological innovation and ecological awareness. Such tools invite musicians to explore both sonic and natural territories. The field would benefit from continued exploration of how different natural systems might inform musical interface design, as well as development of better suited frameworks for the evaluation of the biomimetic approaches' effectiveness in creative contexts.

The evaluation process itself demonstrated the value of multi-dimensional assessment criteria for biomimetic systems, incorporating technical performance, conceptual integrity, educational effectiveness, and creative potential. Future evaluations of similar systems might benefit from longitudinal studies that assess how user understanding and appreciation of biomimetic systems evolve over extended periods of interaction. Moreover, traditional software evaluation metrics prove insufficient for creative tools where exploration, expression, and meaning-making are primary objectives rather than task completion or efficiency.

Overall, Sporadic successfully demonstrated the viability and value of biomimetic approaches to instrument design while identifying key principles and challenges that can inform future work in this emerging field. The project's achievements in balancing ecological inspiration with musical functionality provide a foundation for continued exploration of how natural systems can inspire and inform the creation of expressive musical technologies.

6.1 Future Work

The current implementation, while promising, presents several limitations that warrant further investigation. The most immediate opportunity for enhancement lies in the expansion of the visual component to a more professional and intuitive level. The evaluation clearly demonstrated that visual representation is crucial for user understanding and engagement with biomimetic systems, yet Sporadic's current visual design remains relatively basic compared to the sophistication of its underlying ecological model.

Enhanced visualisation could significantly improve observability of the system state and ensure the viability of musical gestures. This can be ensured by providing real-time feedback about system states, parameter relationships, and the temporal scales at which different ecological processes operate. For example, using colour coding to indicate the current temporal scale (sub-100 ms, note or phrase) could help users understand when and why certain changes are occurring, addressing one of the key usability challenges identified in the evaluation. Such visual enhancements would also aid the instrument's use in performance contexts, where better visual feedback could enable more spontaneous and confident interaction with Sporadic's complex parameter space.

On this note, improved visual design for live use would also open pathways for porting Sporadic to different form factors. This includes guitar pedals, synthesizer modules, or desktop effects units. Each of these implementations would offer distinct tactile interaction possibilities that could complement or enhance the ecological metaphors underlying the system. A modular synthesizer implementation could double down on the interconnected, network-based characteristics of mycelial systems, while a desktop unit could propose novel means of interacting with performance-forward aspects of the design, such as the stretch and fold.

Regardless of the chosen form factor, the number of controls could be streamlined to improve accessibility while maintaining the system's conceptual richness. This could be achieved through a tiered interface design which prominently presents essential controls while providing access to advanced parameters through an advanced view. Such an approach would address the feedback from users who found the current interface overwhelming while preserving the system's capacity for deep exploration and complex musical expression.

The implementation of presets and state recall functionality represents another important area for future development, despite the apparent contradiction with the "biological" design philosophy and the desire to avoid coercing the modelled ecosystem. This tension could be resolved through creative approaches that maintain biological authenticity while providing practical functionality. For instance, presets could be conceived as different "seasonal states" or "ecosystem configurations" that reflect natural variations in forest systems over time. Alternatively, the system could provide "seed" states that establish initial conditions while allowing the ecological model to evolve naturally from those starting points.

Further research opportunities exist in exploring different biological systems as sources of inspiration for musical interface design. The success of the forest ecosystem approach suggests that other complex natural systems—such as ant colonies, weather patterns, or cellular processes—might offer equally rich metaphors for musical interaction. Each biological system would present unique challenges and opportunities for parameter mapping, temporal scaling, and interface design.

The development of more sophisticated evaluation frameworks specifically designed for biomimetic instruments represents another crucial area for future investigation. While this project adapted existing NIME evaluation approaches, the unique characteristics of biomimetic systems warrant specialized assessment methodologies that can better capture their multi-dimensional nature and long-term impact on user understanding and creativity.

Longitudinal studies would be particularly valuable for understanding how users' relationships with biomimetic instruments evolve over extended periods of interaction. Such research could reveal whether the educational and conceptual benefits of biomimetic approaches compound over time, and how users' understanding of both the ecological systems and their musical applications deepens through continued engagement.

Finally, future work could explore the potential for biomimetic instruments to serve as research tools for understanding the natural systems they model. The process of creating musical interfaces based on ecological principles might reveal new insights about the systems themselves, creating bidirectional relationships between biological research and musical interface design. Such approaches could contribute to both the advancement of biomimetic instrument design and the broader understanding of the natural systems that inspire them.

The foundation established by Sporadic provides a robust platform for pursuing these diverse research directions, each of which could contribute to the continued development of biomimetic approaches as a significant paradigm within the broader field of musical interface design.

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Appendix A

Design Tools and Platforms

The following list has been compiled in order to make an educated decision on what toolset/platform to target for this project. The notes are related to my personal experience (or lack thereof) with the individual approaches.

1. Code (C/C++/Python/Rust)

   + most control
   + free
   + easiest to roll your own extensions
   + in theory most portable
   + many open source libraries
   + export to: VST/all HW platforms

   - least visual feedback
   - might require most work to get to a basic playable state

2. Max/MSP

   + Pretty much an industry standard
   + big library of functions
   + API for custom extensions
   + many examples out there
   + good sound quality
   + good documentation

   - learning curve due to lower level nature
   - costly

    - Not great for deployment

3. PureData
    + like Max, but free
    + big library of functions
    + API for custom extensions
    + many examples out there
    + big community
    + can embed VSTs in patches
    + export to: compiled C code using the Heavy compiler - Bela/Daisy support

    - sound quality-wise not as good as Max
    - learning curve due to lower level nature
    - Polyphonic MIDI apparently difficult to integrate nicely (?)

4. PlugData
    + PD, but Max-ified with better graphics
    + API for custom extensions
    + in theory supersedes vanilla PD
    + export to: VST/JUCE/all HW platforms

    - same downsides as PD

5. Faust
    + like coding languages above, but procedural
    + big library of functions
    + graphical representation of patches
    + big community
    + export to: Juce/VST/Bela/Daisy/VCV Rack - probably best of all

    - somewhat small community
    - fewer examples
    - learning curve due to exotic language

6. Reaktor

+ Pretty much an industry standard (because NI)
+ big (biggest?) library of functions
+ includes code environment for custom extensions
+ many examples available for free
+ covers the entire span of abstractions (high level/Blocks + functional building blocks/Core + low level code)
+ good sound quality
+ good documentation

- pretty steep learning curve
- coding apparently difficult to get into (like Faust?)
- dying product
- closed environment
- NI in general is fading away

7. Hise

   + free/open source alternative to Reaktor
   + covers the entire span of abstractions (high level blocks + functional building blocks + low level code)
   + open source, so even the core is modifiable/extendable through C++

   - more focus on sampling
   - still a young ecosystem, so you won't find everything in there

8. VCV Rack/Cardinal (or Softube, Cherry Modular environments)

   + alternatives to Reaktor Blocks
   + great library of modules available

   - each module runs as a kind of VST, so no zero-latency designing possible
   - Some modules come at an extra cost

9. Bitwig (esp. Grid)

   + Big focus on modulation and interconnectivity
   + Grid is kind of their Reaktor/VCV/Max alternative
   + Great sketchbook environment

+ can embed VSTs in patches

- Expensive as you are also buying a DAW
- Not extensible with custom code (only if built as VST)
- Cannot export to anything else

10. Drambo

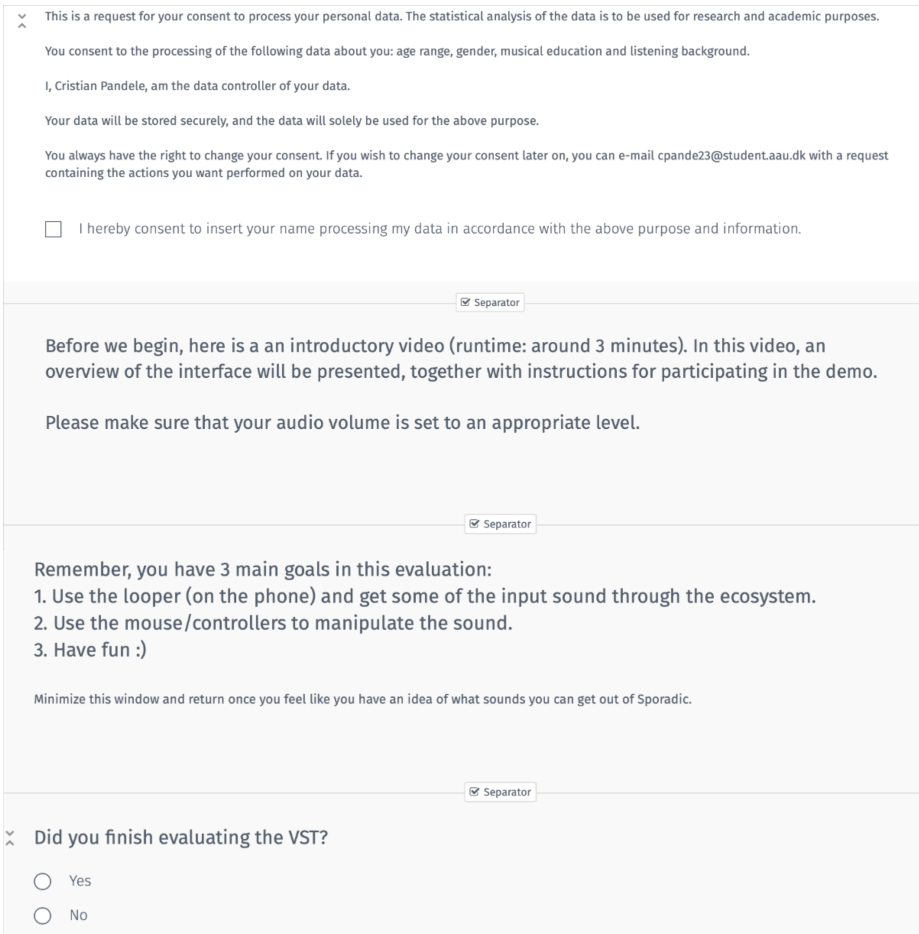
+ Similar to VCV, Bitwig Grid, etc.
+ iPad-based (also a con)
+ cheap, but not free
+ good library of modules
+ simplified approach to patching
+ can embed AUv3 components in patches
+ good for sketching, perhaps?

- iPad-based, so not a "serious" environment
- More focus on grooveboxes, sequencers, etc.
- Limited to the Apple ecosystem, no exporting

Appendix B

Evaluation Survey

The survey questions used for user evaluation are shown below:



This is a request for your consent to process your personal data. The statistical analysis of the data is to be used for research and academic purposes.

You consent to the processing of the following data about you: age range, gender, musical education and listening background.

I, Cristian Pandele, am the data controller of your data.

Your data will be stored securely, and the data will solely be used for the above purpose.

You always have the right to change your consent. If you wish to change your consent later on, you can e-mail cpande23@student.aau.dk with a request containing the actions you want performed on your data.

☐ I hereby consent to insert your name processing my data in accordance with the above purpose and information.

Separator

Before we begin, here is a an introductory video (runtime: around 3 minutes). In this video, an overview of the interface will be presented, together with instructions for participating in the demo.

Please make sure that your audio volume is set to an appropriate level.

Separator

Remember, you have 3 main goals in this evaluation:
1. Use the looper (on the phone) and get some of the input sound through the ecosystem.
2. Use the mouse/controllers to manipulate the sound.
3. Have fun :)

Minimize this window and return once you feel like you have an idea of what sounds you can get out of Sporadic.

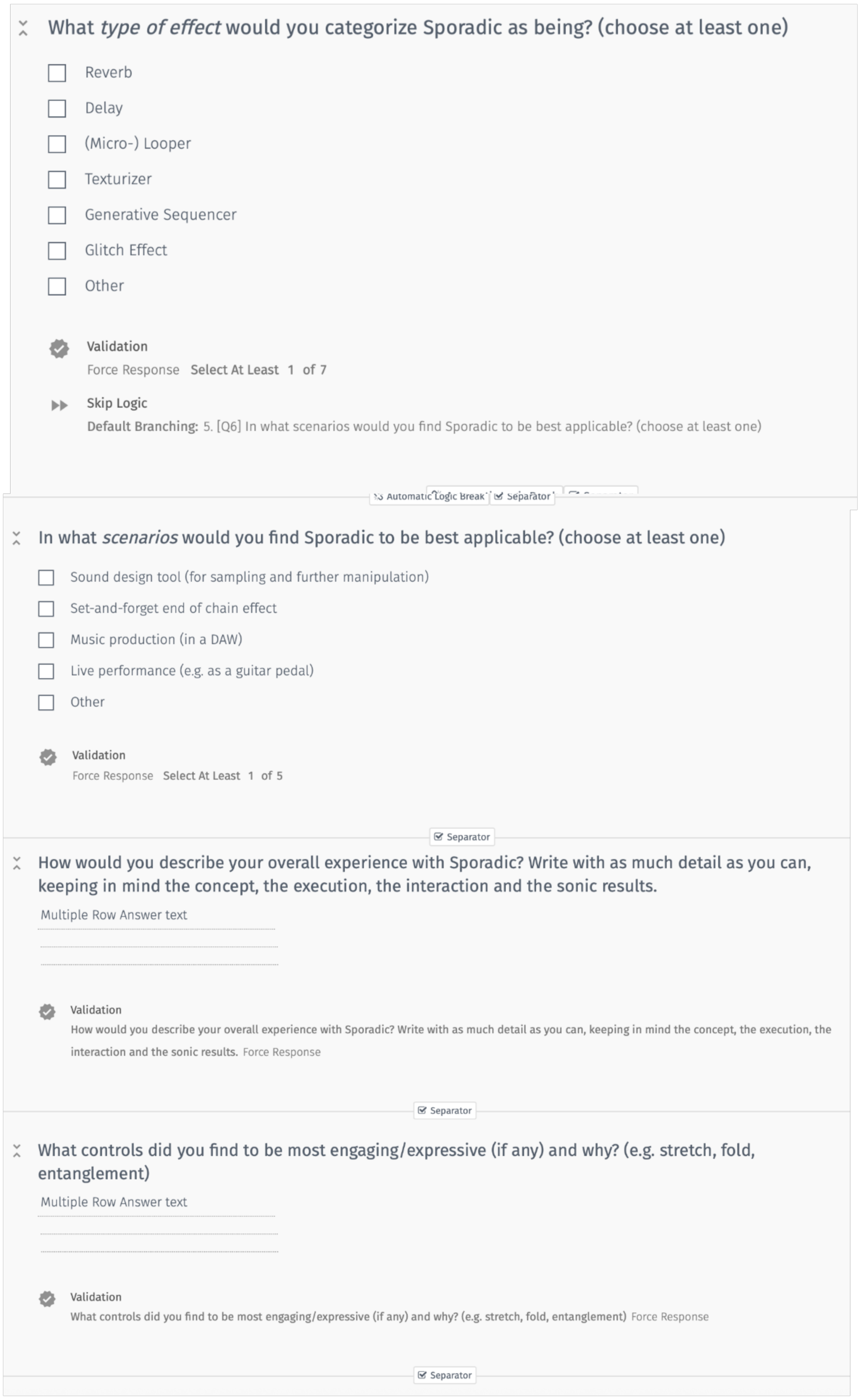
Separator

Did you finish evaluating the VST?

○ Yes

○ No

Figure B.1: Survey Questions 1-4



What *type of effect* would you categorize Sporadic as being? (choose at least one)

- ☐ Reverb
- ☐ Delay
- ☐ (Micro-) Looper
- ☐ Texturizer
- ☐ Generative Sequencer
- ☐ Glitch Effect
- ☐ Other

Validation
Force Response **Select At Least 1 of 7**

Skip Logic
Default Branching: 5. [Q6] In what scenarios would you find Sporadic to be best applicable? (choose at least one)

In what *scenarios* would you find Sporadic to be best applicable? (choose at least one)

- ☐ Sound design tool (for sampling and further manipulation)
- ☐ Set-and-forget end of chain effect
- ☐ Music production (in a DAW)
- ☐ Live performance (e.g. as a guitar pedal)
- ☐ Other

Validation
Force Response **Select At Least 1 of 5**

Separator

How would you describe your overall experience with Sporadic? Write with as much detail as you can, keeping in mind the concept, the execution, the interaction and the sonic results.

Multiple Row Answer text

Validation
How would you describe your overall experience with Sporadic? Write with as much detail as you can, keeping in mind the concept, the execution, the interaction and the sonic results. Force Response

Separator

What controls did you find to be most engaging/expressive (if any) and why? (e.g. stretch, fold, entanglement)

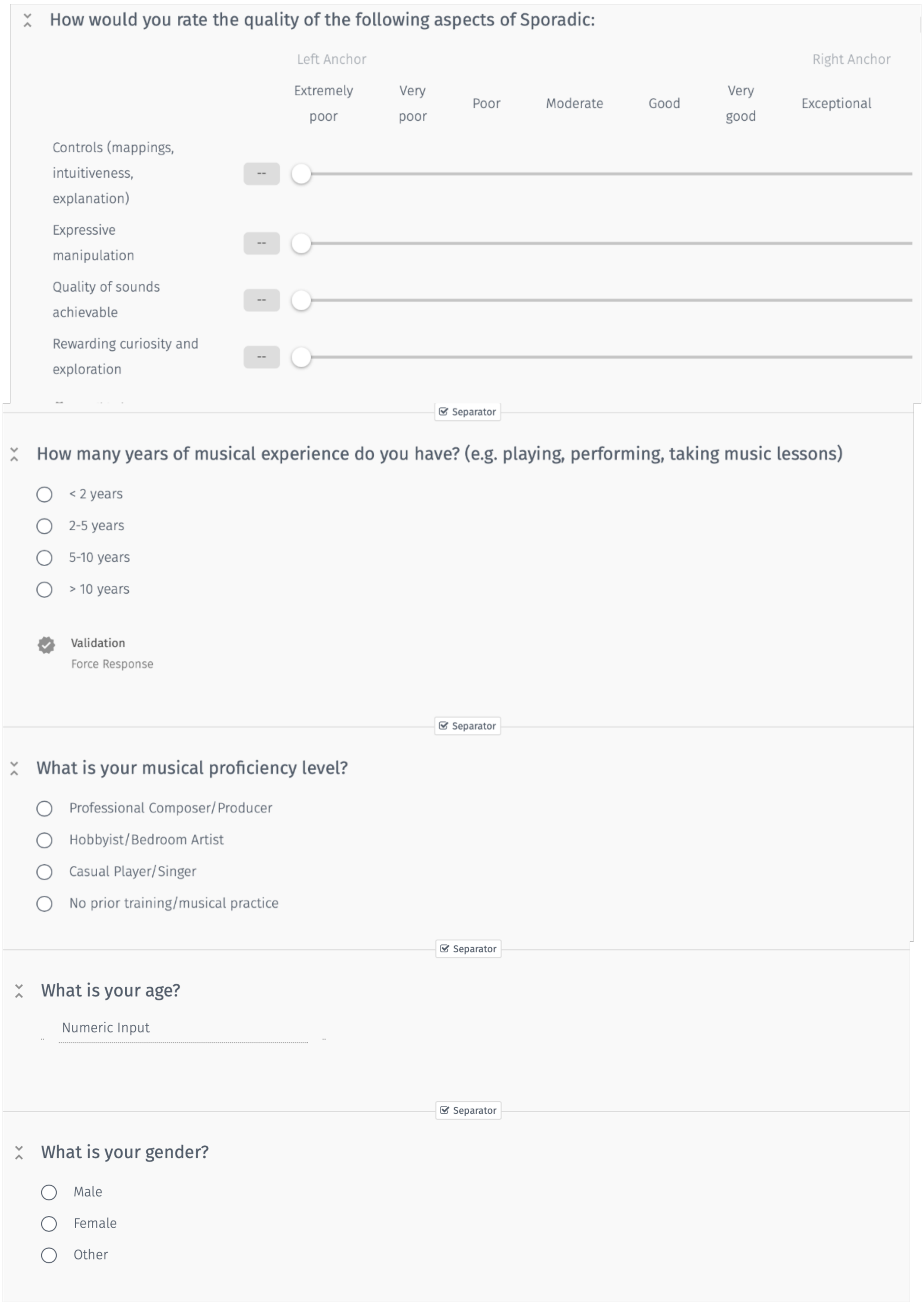
Multiple Row Answer text

Validation
What controls did you find to be most engaging/expressive (if any) and why? (e.g. stretch, fold, entanglement) Force Response

Separator

Figure B.2: Survey Questions 5-8

Figure B.3: Survey Questions 9-12



How would you rate the quality of the following aspects of Sporadic:

	Extremely poor	Very poor	Poor	Moderate	Good	Very good	Exceptional
	Left Anchor						Right Anchor
Controls (mappings, intuitiveness, explanation)	--						
Expressive manipulation	--						
Quality of sounds achievable	--						
Rewarding curiosity and exploration	--						

Separator

How many years of musical experience do you have? (e.g. playing, performing, taking music lessons)

- < 2 years
- 2-5 years
- 5-10 years
- > 10 years

Validation
Force Response

Separator

What is your musical proficiency level?

- Professional Composer/Producer
- Hobbyist/Bedroom Artist
- Casual Player/Singer
- No prior training/musical practice

Separator

What is your age?

Numeric Input

Separator

What is your gender?

- Male
- Female
- Other

Figure B.4: Survey Questions 13-17