# Ninefold: A Distributed Resonant Field

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## Abstract

Edgard Varèse described music as "organized sound." and Iannis Xenakis, in collaboration with Le Corbusier, developed spatial systems in which sound, form, and movement are composed as a single environment. Building on this framework and lineage, *Ninefold* treats composition as an organizational system where architecture, music, and fabrication converge through relational interactions among frequencies, surfaces, and bodies.

The installation constructs a spatial field in which sound and form operate as co-constitutive systems. A harmonic spectrum of nine interdependent overtones ranging 50–1800 Hz generates evolving combinatorial polyrhythmic textures that converge and disperse across space. Sourced from everyday waste, recycled plastic becomes the material substrate for the additive fabrication of nine acoustic mediators designed to hold and redirect sonic energy. Acoustic structure, geometric variation, and material behavior converge through distinct artifacts to produce an immersive harmonic field shaped by sonic gradients. Subtle shifts in geometry produce perceptible differences in acoustic response, establishing gradients (propagation, diffusion, reflection, and concentration) rather than boundaries. Different modules selectively bias the spectrum: elongated and tighter cavities amplify upper bands (800–1800 Hz), producing softer, while flared volumes and smoother interiors reinforce low–mid frequencies (50–400 Hz), yielding fuller, more resonant output. Intermediate ribbed geometries introduce localized reflections, accentuating midrange bands (400–800 Hz), generating an array of difference tones and subtle beats experienced through movement.

*Ninefold* composes an environment where artifacts function as sonic and visual bodies. Listening becomes embodied and situated, unfolding as a temporal sequence of encounters shaped by position and proximity rather than fixed composition.

**Keywords**: *design, fabrication, perception, computation*

## 1. Introduction

Edgard Varèse's understanding of sound organization challenged conventional notions of musical structure by positioning rhythm not as a sequence of measured beats, but as the relational force that gives form, continuity, and coherence to sonic events (Varèse, 1966). A parallel understanding of relational organization appears in Christopher Alexander's observation that "the life that happens in a building or a town is not merely anchored in the space but made up of the space itself" (Alexander, 1979). Both perspectives highlight the significance of an active system unlike a passive container or an instrument through which relationships and experiences emerge. Extending this idea into the acoustic realm, Blesser and Salter (2007) argue that, just as visual qualities contribute to the perception and identity of architectural spaces, aural characteristics fundamentally shape how environments are perceived, experienced, and remembered. In this expanded understanding of space, sound is not a secondary attribute applied to physical objects, but an active medium through which environments are formed. Within this multidisciplinary context, *Ninefold* extends the question: How can distributed resonant bodies and harmonic systems be physically instantiated to shape and reshape sonic perception and spatial listening experiences?

Departing from the visual emphasis of architectural representation (Vorländer, 2008) and extending computational design approaches toward performance-based systems, *Ninefold* investigates how harmonic relationships can be expressed through distributed

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resonant bodies and perceived as evolving spatial phenomena. Following Xenakis's integration of mathematical structures, composition, and spatial sound (Xenakis, 2008), the Philips Pavilion demonstrated how distributed sound systems could transform architecture into an immersive acoustic environment. *Ninefold* reverses this model: instead of embedding speakers within a constructed space, it organizes resonant artifacts as the spatial generators of the sound field.

*Ninefold* comprises nine large-scale resonant artifacts arranged in a three-by-three field and activated by a sixty-minute sound composition. The installation explores time as both a material record and an acoustic experience. Fabrication traces remain embedded in the artifacts, while the composition unfolds through temporal transformation and recurring alignments. As listeners move through the space, changing perspectives reveal distinct resonances, demonstrating that sonic experience emerges through the interaction of sound, material, space, and listener.

The design workflow and the artifacts relate frequency, wavelength, and morphology through variations in volume, cavity configuration and surface articulation. The artifacts establish differentiated acoustic behaviors across the resonator family through controlled spatial and material variations. This method directly extends research reported by Patel and Patel (2026), demonstrating that tailored additive-manufacturing toolpaths, deposition densities, air cavities, and local-to-global surface textures can differentiate reflection, diffusion, and absorption while retaining the same base material. Beyond surface articulation, each artifact is fabricated on a Gigabot using pellet-based additive manufacturing. A custom feedstock of recycled and virgin PLA is developed to meet geometric and acoustic requirements, advancing research on recycled plastics and circular material systems (Kwon, 2025; Kwon, 2026). Together, geometry, material composition, and fabrication operate as interconnected acoustic drivers, allowing harmonic relationships to be expressed not only through sound, but through the physical behavior of the resonators themselves.

*Ninefold* demonstrates how a single harmonic structure can generate coherent temporal, resonant, material, fabricated, and perceptual expressions across multiple domains. The resulting environment emerges through the interaction between harmonic bodies, listener movement, and acoustic perception, where changing viewpoints produce different experiences of resonance and spatialization.

## 2. Acoustics as Design Experience

Blesser and Salter describe *aural architecture* as the shaping of space through sound, where acoustic phenomena influence perception as profoundly as physical form. This framework provides the theoretical foundation for examining acoustics as a generative component of architectural design rather than merely a criterion for acoustic optimization.

### 2.1 Design Layout

Building on the conceptual idea of *aural architecture* and generative soundscapes, *Ninefold* investigates acoustics as an active design medium through a three-by-three array of responsive artifacts that collectively generate an evolving resonant environment.

### 2.2 Music Composition

The *Ninefold* composition is structured as a continuous 60-minute sound cycle exploring evolving textures, polyrhythmic relationships, and emergent acoustic phenomena. Its primary material is a 34-note self-replicating palindromic melody:

*0 1 2 3 4 3 5 6 2 7 5 6 8 1 8 7 4 0 4 7 8 1 8 6 5 7 2 6 5 3 4 3 2 1*

Each integer corresponds to one of nine harmonic frequencies assigned to the ceramic resonators, representing harmonic identities rather than conventional pitch classes. The melody's defining feature is its recursive temporal structure, with simultaneous iterations occurring at tempo ratios of 13:1 and 21:1. These layered cycles create periodic alignments in which the melody re-emerges across multiple temporal scales, producing recurring meta-melodic relationships through the interaction of the two tempi. Figure 1 visualizes this process, highlighting the 21:1 layer in red, 13:1 layer in cyan, overlapping events in black, and emergent meta-melody.

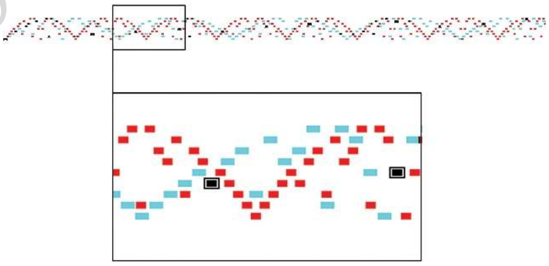

**Figure 1**. Temporal structure of the self-replicating melody.

This principle forms the structural foundation of the entire 60-minute cycle. Variations are introduced through changing articulations, sustained resonances, pulsed events, and evolving textural densities, while the underlying temporal framework remains constant. The selection of a 34-note melody was motivated by its relationship to the Fibonacci sequence. The temporal ratios of 13:21 arise naturally from consecutive Fibonacci numbers within a melody whose total length is also a Fibonacci number (34). Since each Fibonacci number is obtained by summing the two preceding values (0, 1, 1, 2, 3, 5, 8, 13, 21, 34, ...), the simultaneous presence of the ratios 13:21 within a 34-note structure provides an elegant proportional framework that informs the temporal organization of the composition.

*2.2.1 Harmonic Structure*
The harmonic framework is based on nine fundamental frequencies:

50 Hz, 100 Hz, 150 Hz, 200 Hz, 300 Hz, 450 Hz, 600 Hz, 900 Hz, and 1800 Hz.

These frequencies are generated as multiples of 50 Hz from the set (1, 2, 3, 4, 6, 9, 12, 18, 36), corresponding to the resonant characteristics of the artifacts. Throughout the composition, individual resonators are introduced with subtle frequency offsets from their nominal values, creating acoustic beating between neighboring frequencies. Since beat frequency is determined by the difference between interacting tones, the perceived pulsation varies according to the harmonic being excited. Each frequency is paired with a detuned counterpart using its multiplier as the offset (e.g., 150 Hz becomes 153 or 147 Hz). These controlled deviations later produce precise pulse relationships and layered polyrhythmic structures derived from the same multiplier system.

*2.2.2 Wave Interference*
Frequency beating occurs when two tones with closely spaced frequencies interact, producing a perceived amplitude modulation at a rate equal to the difference between their frequencies.

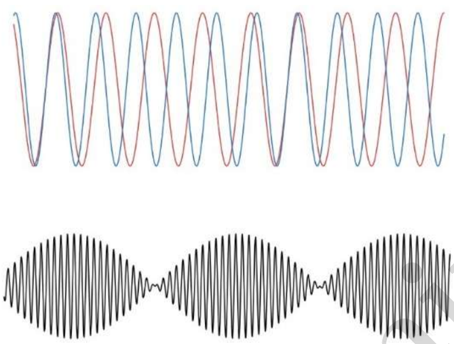

**Figure 2**. Temporal structure of the self-replicating melody (Top: sine wave offset by 2Hz; Bottom: perceived amplitude modulation).

The first examples show two sine waves separated by a frequency difference of only 2 Hz, while the final illustration presents the resulting amplitude modulation perceived by the listener. Similar interference patterns occur throughout *Ninefold* using a range of carefully controlled detuning offsets, producing continuously shifting pulses, textures, and spatial interactions.

*2.2.3 Wireless Networking*
Each artifact incorporates a tablet wirelessly connected to a local network within the exhibition space (Fig. 3). The tablets generate synchronized visual and auditory outputs based on their position in the installation and the underlying musical composition.

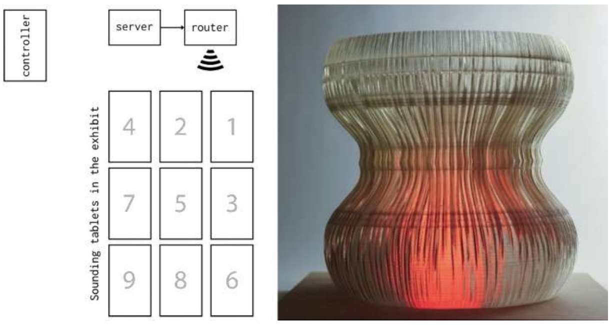


**Figure 3**. Left: networked tablets enabling synchronized audiovisual output; Right: audiovisual output.

A *Raspberry Pi* server synchronizes the performance by transmitting timing data, while each tablet independently controls synthesis parameters such as waveform, frequency, duration, and pulsing. A dedicated control tablet manages only start and stop functions to preserve timing reliability. The local network also enables audience participation through QR-based input, adding distributed background textures that enrich the audiovisual composition while maintaining structural coherence.

## 3. Design Fabrication

The physical design of *Ninefold* translates harmonic composition into a family of acoustically differentiated resonators. Rather than creating independent objects, the project develops a shared geometric language, fabrication strategy, and material system that transform musical organization into physical form. Geometry defines relationships among resonators, while additive manufacturing and recycled plastic enable their realization, material performance, and visual continuity across the installation.

### 3.1 Module Design

Each resonator in Ninefold is derived from a common family of continuously evolving reaction–diffusion curves that serve as the primary geometric language of the project (Fig. 4).

This approach allows every resonator to maintain a recognizable formal identity while accommodating different acoustic behaviors across the harmonic spectrum. Reaction–diffusion curves are used as the common geometric language for the resonator family. The continuously evolving curves are transformed into sectional profiles that establish a shared formal vocabulary while allowing controlled variation in cavity geometry, acoustic pathways, and openings. The reaction–diffusion curves are translated into sectional profiles and modified through variations in radius, curvature, folding, spacing, and vertical progression. These evolving sections are lofted to form enclosed chambers, waists, funnels, helical passages, ribbed surfaces, and acoustic openings that shape each module's resonant behavior. Although all resonators derive from the same generative system, their formal

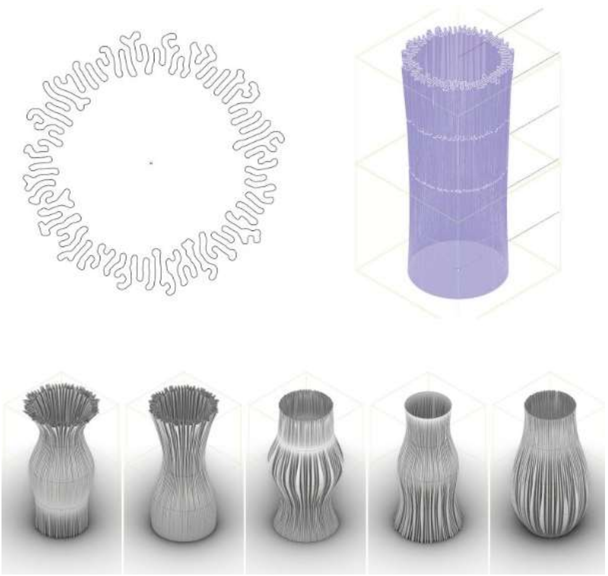

**Figure 4**. Reaction–diffusion curves as a shared geometric language for the resonator family, generating sectional profiles with controlled variation in cavity geometry, acoustic pathways, and openings.

differences result from continuous geometric transformation. The transformations generate nine resonators tuned to the harmonic frequencies of the sixty-minute composition, spanning 50 Hz to 1800 Hz (Table 1). Lower-frequency resonators feature larger enclosed volumes and longer acoustic pathways, while higher-frequency forms become smaller with narrower openings and more intricate sectional geometries (Fig. 5).

**Table 1.** Design parameters of nine resonators, including harmonic frequency assignments, geometric variations, cavity configurations, and physical dimensions.

| Artifact | Height (mm) | Acoustic Profile | Design Parameter |
|---|---|---|---|
| H1 | 2286 | Reinforce low Hz | Long large volume |
| H2 | 1818 | Deep bass | Exponential Horn |
| H3 | 1603 | Upper bass | Helical tunnel |
| H4 | 1338 | Lower bass | Bulbous chamber |
| H5 | 1324 | Low mid-range | Flared; mid-waist loose |
| H6 | 1571 | Mid-range | Ribbed conical; mid waist tight |
| H7 | 910 | Upper mid-range | Pleated funnel; tight base |
| H8 | 901 | Presence | Helical torso; deeper ribs |
| H9 | 457 | Brilliance | Multi-rings/ waists |

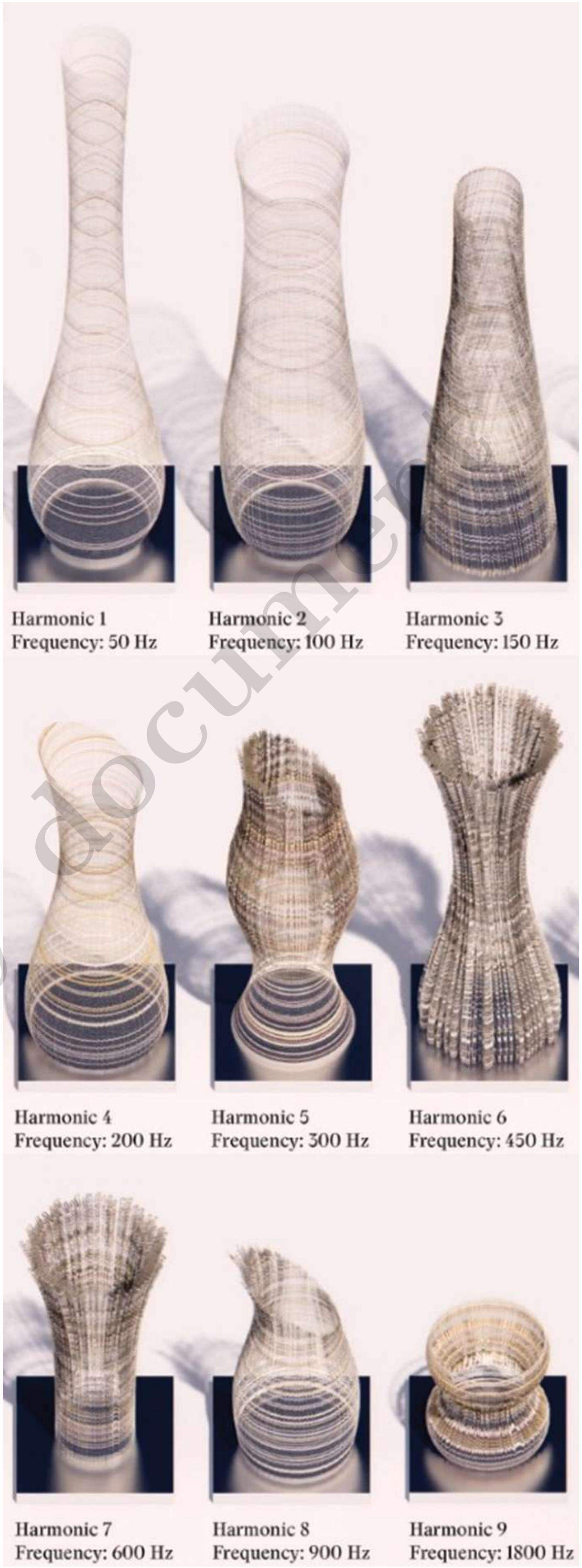


**Figure 5**. Resonant geometries developed for *Ninefold*. Nine 3D-printed resonators derived from a shared reaction–diffusion system span harmonic frequencies from 50 Hz to 1800 Hz. Variations in cavity geometry and material composition create distinct acoustic responses while maintaining a unified design language.

### 3.2 Module Fabrication

The resonators were fabricated at architectural scale using pellet-based additive manufacturing on a Gigabot platform (Fig. 6). Pellet extrusion enabled large hollow shells with continuously varying sectional geometries while maintaining uninterrupted internal acoustic pathways.

**Figure 6**. Pellet-based extrusion fabrication of a Harmonic Artifact 9 using a Gigabot additive manufacturing system.

Compared to filament-based printing, the larger build volume allowed fabrication of larger modules, enabling resonators ranging from 457 mm to 2286 mm in height to be assembled from fewer printed components. To accommodate fabrication constraints, resonators were segmented into modular components (Fig. 7), enabling assembly of full-scale artifacts within the printer's maximum build volume.

**Figure 7**. Modular fabrication strategy for Harmonic Artifact 1.

Fabrication, toolpaths, wall thickness, and deposition strategies were coordinated with each artifact's intended resonant behavior, allowing fabrication and structural parameters to actively contribute to acoustic performance rather than merely reproduce geometry.

### 3.3 Module Material: Recycled Plastic

Recycled plastic was incorporated as an integral component of the overall design system rather than solely as a sustainable fabrication material. Across the resonator family, the proportion of recycled PLA gradually increases from 10% to 50%, while virgin PLA decreases accordingly (Fig. 8 and Table 2).

**Figure 8**. Circular PLA workflow from discarded prints (Left) to recycled feedstock (Center) and pellet-based extrusion fabrication (Right) of a harmonic artifact on a Gigabot system.

**Table 2.** Comparison of material composition.

| Artifact | Virgin PLA | Recycled PLA |
|---|---|---|
| H1 | 90 | 10 |
| H2 | 85 | 15 |
| H3 | 80 | 20 |
| H4 | 75 | 25 |
| H5 | 70 | 30 |
| H6 | 65 | 35 |
| H7 | 60 | 40 |
| H8 | 55 | 45 |
| H9 | 50 | 50 |

This progressive material composition creates variations in translucency, opacity, and chromatic density that visually correspond with the harmonic spectrum. Rather than assigning colors to specific frequencies, the installation employs a continuous material gradient to unify the resonators as a cohesive family. This material strategy builds upon previous investigations into recycled thermoplastics for large-scale additive manufacturing (Kwon, 2025) while extending those studies toward acoustically functional resonant surfaces. Geometry, fabrication, material, and resonance function as an integrated design system, expressing harmonic relationships through sound, form, and visual material qualities.

## 4. Acoustic Tests and Spatial Behavior

Spatial audio measurements evaluated sound distribution and listener experience throughout the installation. A custom recording workflow captured the evolving harmonic composition at multiple locations.

### 4.1 Measurement Workflow

To characterize the spatial acoustic response of the installation, the complete audio composition was recorded at multiple listening locations within the exhibition space (Fig. 9). A custom MATLAB GUI script was developed to automate the recording process using an audio interface configured for dual-channel acquisition. Two microphones were connected to the interface and recorded synchronously at a sampling frequency of 48 kHz, preserving high-fidelity audio.


**Figure 9**. Spatial acoustic measurement locations within the exhibition space.

The script automatically detected the audio interface, initiated recording after a countdown, and captured the performance using consistent acquisition settings. Recordings from each microphone were exported as separate WAV files for analysis. Waveforms were generated for visual inspection, while signals were converted to decibel scale and analyzed in Room EQ Wizard (REW) to produce spectrograms for spectral evaluation.

### 4.2 Spatial Findings

Measurements were repeated at selected listening locations using consistent microphone orientation and input gain for comparability (Fig. 10).

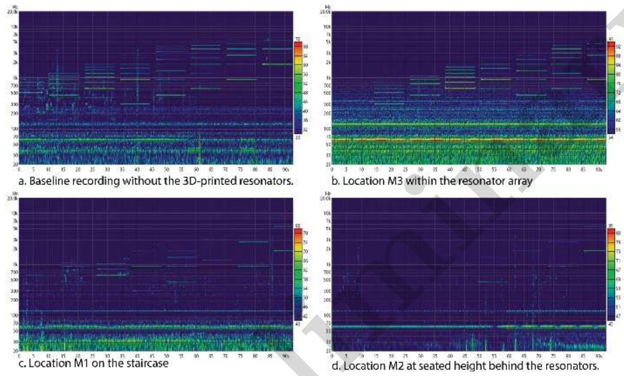


**Figure 10**. Spectrograms of the *Ninefold* composition recording Harmonics 1 through 9 in the exhibition space.

Spectrograms analyzed how the installation geometry and venue acoustics affected resonance and harmonic distribution. In each spectrogram, the x-axis represents time, the y-axis frequency, and color intensity indicates sound pressure level. The variations create distinct acoustic zones for reflection, diffusion, and sound redirection. Location M3 records the highest sound pressure levels across all harmonics, indicating stronger acoustic energy within the resonator field. In contrast, M1 and M2 show lower levels, confirming uneven resonance distribution. As listeners move through the installation, shifting resonances and beating patterns create a dynamic listening experience. The sound field therefore changes across space and time, revealing different harmonic relationships over the sixty-minute composition.

## 5. Conclusion

*Ninefold* contributes a computational methodology for creating an evolving resonant environment in which audiovisual behavior continuously changes in response to harmonic progression and the listener's movement through space. The installation reveals multiple perspectives of time: the artifacts preserve a visible history of their fabrication, much like geological layers record processes of formation, while the sixty-minute composition unfolds through a linear temporal sequence. Visitors simultaneously encounter time as a static material record and as an evolving sonic process, with each listener's position, movement, and auditory perception producing a distinct experience of the resonant field. Through these relationships, *Ninefold* develops an integrated acoustic system in which sound, matter, and perception evolve together.

## 6. Acknowledgments

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