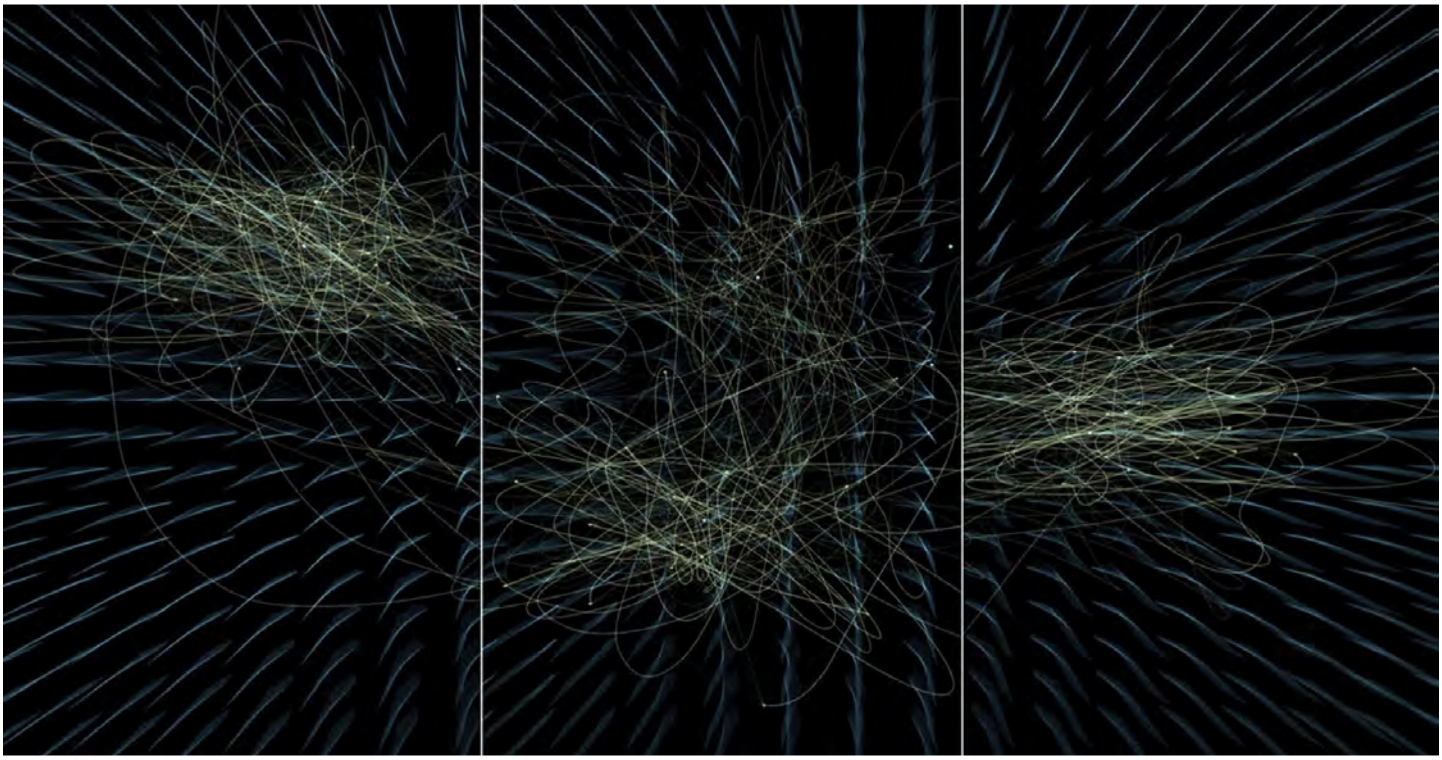
xCoAx 2026
Torino, Italy
2026.xCoAx.org

Ninefold: Bridging Mathematical Abstraction and Phenomenal Reality



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Ninefold is an audiovisual artwork that explores how a high-dimensional mathematical space can be made perceivable. It uses a nine-dimensional flocking simulation to control the generation of audio and visuals. The installation presents three screens showing graphical renderings of different three-dimensional subspaces. Agent positions and velocities are mapped to parameters of sound synthesis systems based on modal synthesis and feedback delay networks. The installation provides minimal interaction by allowing visitors to freeze selected dimensions. This reduces the dimensionality of the simulation and causes certain aspects of the generated audio and visuals to become static. By coupling the manipulation of spatial dimensions with their visual and acoustic consequences, the work aims to bridge mathematical abstraction and phenomenal reality.

Keywords: Audiovisual Installation, Generative Art, Flocking Simulation, Sound Synthesis.

DOI 10.34626/2026_xcoax_036

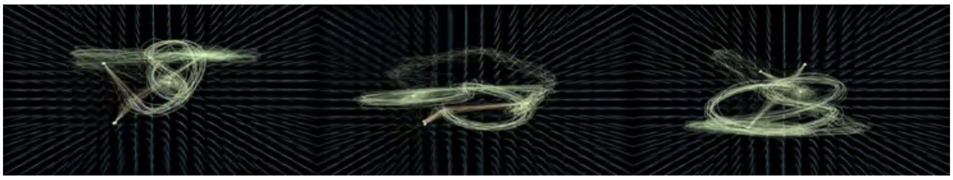

Fig. 1. *Ninefold* flocking visualisations. The graphical renderings show three different three-dimensional views of the nine-dimensional flocking simulation. The dimensions shown are (from left to right): 1–3, 4–6, 7–9.

Description

Ninefold is an audiovisual artwork that employs a simulation of flocking behaviour that runs in a nine-dimensional space. It invites visitors to engage with ideas that lie beyond phenomenal reality, since nine dimensions describe a space that is mathematically coherent yet inaccessible to human senses and spatial imagination.

Flocking behaviour refers to the collective movement exhibited by groups of animals, such as birds or fish, in which individuals coordinate their direction and speed with those of their neighbours. Craig Reynolds contributed significantly to this field by developing Boids, a multi-agent system that simulates flocking behaviour through simple rules governing evasion, cohesion, and alignment among agents (Reynolds 1987).

Flocking simulation is one of the artificial life algorithms that has frequently been used to generate music. By mapping properties of the flock, such as agent positions, agent velocities, or inter-agent distances to sound synthesis parameters, the dynamics of flocking behaviour and especially its emergent group behaviour are rendered audible. *Ninefold* continues the authors' earlier works based on flocking simulations (Bisig and Kocher 2012; 2013; Schacher et al. 2014).

In a general sense, the flocking simulation is a numerical algorithm based on a mathematical formalism. When all behaviours are accurately quantified, this formalism can be used to simulate a real-world phenomenon. There is no inherent limitation preventing us from expanding this simulation by inventing hypothetical behaviours or applying this formalism to other than three-dimensional spaces. However, it seems that the connection between the simulation and its real-life equivalent is too strong and has limited the extent to which these ideas have been pursued. Only a few examples exist that apply high-dimensional flocking simulations to the creation of music. Tim Blackwell and Michael Young describe the artistic potential of self-organisation inherent in flocking simulation. They describe how the principle could be extended to an N-dimensional space and present two applications, Swarm Music and Swarm Granulator (Blackwell and Young 2004).

Fig. 2. *Ninefold* installation. Left side: schematic depiction of an exhibition setup. Right side: photo of one of the authors testing a first installation prototype.

Ninefold can be presented either as an installation or as a concert performance.

The installation (Fig. 2) consists of three screens, mounted on stands and arranged side by side to form a quarter-circle arc. Each screen displays a distinct three-dimensional view of three of the simulation's nine dimensions, as if the flocks were observed from different spatial "perspectives." At the centre, two pairs of headphones are placed on a stand, allowing two visitors to listen to the generative audio simultaneously. The installation automatically steps through different flocking behaviour presets, resulting in a range of visual and acoustic outcomes.

Each of the three screens is equipped with a prominently placed custom-made button, which provides the only way to interact with the installation. Pressing one of the buttons freezes or unfreezes the dimensions visualised on that screen. When frozen, the corresponding visualisation stops and the audio parameters associated with these dimensions are locked in place. The three buttons can be activated in any combination, allowing visitors to explore the multi-dimensionality selectively. Reducing the dimensionality to three makes the spatial representation easier to grasp as a physical environment, but it also limits the variability of the resulting sonic output. Conversely, increasing the number of dimensions beyond three reduces spatial intuitiveness while enhancing the acoustic richness and complexity.

In the case of *Ninefold* being presented as a performance, it unfolds on stage, featuring visuals that can be displayed either through three video projections or in a split-screen on a single projection. One performer manipulates the flocking behaviour in real time, while another controls and adjusts the mapping of flocking parameters to sound synthesis parameters. This interplay adds a performative quality and complements the more analytical nature of the installation.

Fig. 3. Flocking simulation controlling a feedback network. A video excerpt is available online: https://player.vimeo.com/video/1165135527?h=7eae368fe1

Fig. 4. Flocking simulation controlling modal synthesis. A video excerpt is available online: https://player.vimeo.com/video/1165135512?h=44c90b111a

Technical Details

Simulation

The flocking simulation is programmed in C++ and employs a custom-developed addon[1] for OpenFrameworks. It is a revised version of the original library ISO-flock[2] developed by one of the authors (Bisig et

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1. https://github.com/bisnad/ofxDabFlock
2. http://swarms.cc/downloads/

al. 2008). The simulation is designed to be highly flexible. It allows for an arbitrary number of flocks, each containing any number of agents. It provides a variety of agent behaviours—extending the classical Boids behaviours—and neighbourhood calculations can be carried out on any agent parameter, not just position. All agent parameters can be represented as vectors of any dimensionality. To integrate the simulation into a variety of setups and contexts, it can communicate with other software via OSC. All simulation settings and parameters can be remotely controlled—even in real time, if necessary—while all agent parameters can be sent out to drive a video rendering or sound synthesis software.

The simulation currently used for *Ninefold* takes place in a nine-dimensional space, with all agent parameters (position, velocity, acceleration) represented as nine-dimensional vectors. The simulation space is populated by two flocks having different properties and fulfilling different functions. The first one is a "regular" flock that exhibits not only the classical Boids behaviours (evasion, cohesion, alignment) but also two non-standard behaviours that offer additional levels of control. These extra behaviours include setting a target position to which the agents are attracted or a target velocity, resulting in the agents moving in a specific direction. The second flock is composed of agents that do not move by themselves because they have no behaviours assigned. Therefore, the agents' positions need to be set manually. As the agents of the first, "regular" flock react to all neighbouring agents in the simulation space, the second flock influences the movements of the first flock's agents.

The second flock serves the purpose of establishing various spatial constellations as its agents attract or repel the agents of the "regular" flock, whereby the strength of attraction and repulsion can be varied. The second flock's number of agents and their positions, as well as the "regular" flock's number of agents and settings for the behaviours, define the overall characteristics of the simulation. All these settings can be a set of fixed values, stored and retrieved as presets, or modified in real time to provide an interface for human interaction.

Another core element of the current simulation is the possibility to "freeze" particular dimensions. This means the simulation stops updating certain dimensions of the agents' parameters (position and velocity), so that these parameters remain unchanged along these dimensions. The motivation for this feature is to reduce the cognitive overload involved in understanding an entity that moves in nine dimensions. This is achieved by providing the possibility to switch back and forth between the full set of dimensions and more familiar, intellectually graspable lower-dimensional subspaces.

Visualisation

For the visualisation (Fig. 1), an approach has been chosen that splits the nine dimensions of the simulation into three groups of three dimensions and renders three different 3D views (view 1: dimensions 1–3, view 2: dimensions 4–6, view 3: dimensions 7–9).

Each rendering depicts the agents of the “regular” flock as wireframe pyramids located at their positions and oriented in alignment with the agents’ movement directions. The movement trajectories are shown as polylines in which line segments connect previous agent positions. Neighbourhood relationships are shown as lines connecting the agents.

The agents of the second flock are shown as wireframe spheres located at the agents’ positions and with fixed orientations. In addition, a vector field visualisation is shown with lines extending from regular grid positions and pointing towards the agents, indicating the attracting effect of these agents.

The graphical renderings are designed, on the one hand, to be interpretable as flocking behaviour within a high-dimensional space containing attractors, and, on the other hand, to aesthetically reinforce the concept of a scientific visualisation that conveys the mathematical and physical notions of space.

Sonification

To explore different approaches to render the high-dimensional dynamics of the flocking simulation perceptible, several sonification methods are used. Despite their peculiarities, these methods share the following fundamental similarities. Each agent is represented by a single sound-producing instance that uses the agent’s position and velocity parameters as synthesis parameters. The received nine-dimensional values are organised into groups of three, with each group assigned to dimensions 1–3, 4–6, and 7–9, respectively. By assigning specific aspects or functions of the sound synthesis to each of these groups, they become perceptually differentiable. This organisational structure is designed to maximise the effectiveness of the aforementioned “parameter freezing.”

The sonification methods differ in the specific ways in which the agents’ parameters are interpreted, that is, further processed, averaged, or compared, and mapped to synthesis parameters. They also differ in the sound synthesis technique used: either modal synthesis or a feedback delay network.

In modal synthesis, an excitation signal (such as an impulse or a noise burst) is fed into a bank of resonant filters, each representing a mode of vibration, to reproduce the resonant characteristics of a physical object (Calvet et al. 1990). Here, the nine-dimensional parameters control the filter’s frequencies and bandwidths, and the excitation of the modes is triggered whenever the calculated neighbourhood density exceeds a defined threshold.

A feedback delay network is a synthesis technique that generates complex resonant audio by letting a signal circulate through multiple delay lines arranged in a recurrent network (Bisig and Kocher 2017). Here, the nine-dimensional parameters control the delay times and the signal attenuation in the feedback loops.

Discussion

Ninefold aligns with two central approaches in generative art. First, establishing explicit correspondences between underlying generative principles and their perceptible outcomes, and second, employing a unified generative system to produce synthetic media across multiple modalities. The first approach positions generative processes not as concealed mechanisms, but as primary aesthetic drivers, thereby making them experienceable. The second fosters cross-modal coherence grounded not in surface resemblance but in shared constructive logic.

The installation version of *Ninefold* shows how the intuitive comprehensibility of high-dimensional spaces depends on the chosen experiential and cognitive framing—either as a traversable physical space or as a set of parameters defining a sonic object. When visitors freeze and unfreeze dimensions, they engage with this concept by actively shifting between these two modes of understanding.

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