# Quantum Field Theory Sound Synthesis Framework

Robert B. Lisek*
[robertblisek@gmail.com]
Fundamental Research Lab
Prague, Czech Republic

## Abstract

We present a Quantum Field Theory (QFT) Sound Synthesis Framework that translates quantum phenomena into audible representations. The framework implements five sonification models: Basic QFT Field, Advanced QFT with coupled fields, QFT Lattice, Quantum Fourier Transform, and Path Integral Synthesis. Each model maps specific QFT aspects to audio parameters, enabling both educational exploration and musical composition through quantum concepts.

## CCS Concepts

• **Computing methodologies → Sound synthesis**; *Modeling methodologies*; Physical simulation; • **Applied computing → Sound and music computing**; • **Theory of computation →** *Quantum computation theory*.

## Keywords

quantum field theory, sound synthesis, audio processing, SuperCollider, quantum computing, sonification, quantum states, coherent states, squeezed states, thermal states, path integral formulation, real-time synthesis, parameter mapping

**ACM Reference Format:**
Robert B. Lisek. 2025. Quantum Field Theory Sound Synthesis Framework. In *Proceedings of the ARTECH 12th International Conference on Digital and Interactive Arts (CONFERENCE '25), November 26–28, 2025, Braga, Portugal.* ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

## 1 Introduction

Sound synthesis and quantum field theory share a fundamental connection: both deal with oscillations, waves, and energy distributions across modes. The QFT Sound Synthesis Framework exploits this connection by mapping quantum field theoretical concepts directly to audio parameters.

This framework serves four purposes: (1) providing intuitive, sensory interfaces to abstract quantum concepts; (2) creating new timbral possibilities for electronic music; (3) developing educational tools for understanding quantum phenomena through auditory feedback; and (4) bridging physics and audio synthesis through shared mathematical foundations.

Implemented in SuperCollider for real-time audio synthesis, the framework offers an interactive interface allowing users to manipulate quantum parameters and immediately hear their effects. The system is accessible to both physicists seeking novel representations and musicians exploring new sound design approaches.

## 2 Theoretical Background

### 2.1 Quantum Field Theory Concepts

Quantum Field Theory (QFT) combines quantum mechanics with special relativity to describe subatomic particles through quantized fields. Unlike classical fields, quantum fields exist in quantized states exhibiting superposition, entanglement, and quantum fluctuations.

*2.1.1 Quantum Fields.* A quantum field $\phi(x,t)$ is expressed as:

$$\phi(x,t) = \sum_k \frac{1}{\sqrt{2\omega_k V}} \left( a_k e^{i(kx-\omega_k t)} + a_k^\dagger e^{-i(kx-\omega_k t)} \right) \quad (1)$$

where $a_k$ and $a_k^\dagger$ are annihilation and creation operators, $\omega_k$ is the frequency of mode $k$, and $V$ is the system volume.

*2.1.2 Quantum States.* We implement three fundamental states:

**Coherent States** $|\alpha\rangle$: Minimum uncertainty states approximating classical behavior.

$$a_k|\alpha\rangle = \alpha|\alpha\rangle \quad (2)$$

**Squeezed States** $|r,\theta\rangle$: States with redistributed uncertainty.

$$|r,\theta\rangle = S(r,\theta)|0\rangle = e^{\frac{1}{2}(re^{-i\theta}a^2 - re^{i\theta}a^{\dagger 2})}|0\rangle \quad (3)$$

**Thermal States** $\rho_{\text{th}}$: Mixed states at temperature $T$.

$$\rho_{\text{th}} = \frac{1}{Z}e^{-\beta H} = \frac{1}{Z}\sum_n e^{-\beta E_n}|n\rangle\langle n| \quad (4)$$

where $\beta = 1/k_B T$, $H$ is the Hamiltonian, and $Z$ is the partition function.

*2.1.3 Field Interactions and Fluctuations.* Quantum fields exhibit self-interactions (e.g., $\lambda\phi^3$ or $\lambda\phi^4$ terms in the Lagrangian) and vacuum fluctuations due to the Heisenberg uncertainty principle, represented as noise terms in our models.

## 3 Synthesis Models

We implement five synthesis models, each representing different QFT aspects.

### 3.1 Basic QFT Field

This model represents a single quantized scalar field with self-interactions and quantum fluctuations.

*Correspondence: [robertblisek@gmail.com]


*Conference '25, Braga, Portugal*

ACM ISBN 978-1-4503-XXXX-X/25/06
https://doi.org/10.1145/nnnnnnn.nnnnnnn

*3.1.1 Mathematical Model.*

$$\phi(x,t) = \sum_{k=1}^{N} A_k \sin(\omega_k t + \theta_k) + \lambda\phi^3(x,t) + \eta(x,t) \tag{5}$$

where $N = 32$ oscillators, $A_k$ are state-dependent amplitudes, $\omega_k$ are mode frequencies, $\theta_k$ are random phases, $\lambda$ is self-interaction strength, and $\eta(x,t)$ represents vacuum fluctuations.

Amplitudes depend on quantum state: coherent ($A_k = 1/\sqrt{N}$), squeezed ($A_k = e^{r\sin(2\pi k/N)}/\sqrt{N}$), or thermal ($A_k = \sqrt{T \cdot \text{rand}}/\sqrt{N}$).

*3.1.2 Parameters.* Frequency (base oscillation), Lambda (self-interaction), Quantum Noise (vacuum fluctuations), State Type (coherent/squeezed/thermal), Squeeze Parameter, Temperature, and Detune (frequency spread).

*3.1.3 Sonic Characteristics.* Produces sounds from pure harmonics (low lambda, coherent state) to complex noise textures (high lambda, thermal state). Self-interaction introduces harmonic distortion; quantum noise adds granular texture.

## 3.2 Advanced QFT with Two Fields

This model implements two interacting quantum fields with coupling.

*3.2.1 Mathematical Model.* Two coupled fields:

$$\phi_1(x,t) = \sum_{k=1}^{N} A_{1k} \sin(\omega_{1k} t + \theta_{1k}) + \lambda\phi_1^3(x,t) + \eta_1(x,t) \tag{6}$$

$$\phi_2(x,t) = \sum_{k=1}^{N} A_{2k} \sin(\omega_{2k} t + \theta_{2k}) + \mu\phi_2^3(x,t) + \eta_2(x,t) \tag{7}$$

Output with interaction:

$$\text{output} = \phi_1(x,t) + \phi_2(x,t) + \gamma\phi_1(x,t)\phi_2(x,t) \tag{8}$$

where $\gamma$ is interaction strength.

*3.2.2 Parameters.* Frequency1/2 (base frequencies), Lambda/Mu (self-interactions), Interaction Strength ($\gamma$), State Types, Squeeze Parameters, Temperatures, and Quantum Noise levels for each field.

*3.2.3 Sonic Characteristics.* Creates rich textures where fields interact dynamically. Low interaction preserves individual field character; high interaction creates emergent behaviors with spectral beating and modulation patterns.

## 3.3 QFT Lattice

This model represents quantum fields on a discrete spatial lattice with nearest-neighbor interactions.

*3.3.1 Mathematical Model.* Field at lattice site $i$:

$$\phi_i(t) = A_i \sin(\omega_i t + \theta_i) + J \sum_{\langle i,j \rangle} \phi_j(t) + \eta_i(t) \tag{9}$$

where $J$ is coupling strength and $\langle i,j \rangle$ denotes nearest neighbors. Topologies include 1D chains, 2D grids, and periodic boundaries.

*3.3.2 Parameters.* Lattice Size, Topology (1D/2D/ring), Coupling Strength ($J$), Local Frequencies, State Type, Quantum Noise, and Boundary Conditions.

*3.3.3 Sonic Characteristics.* Creates spatially distributed sounds with wave propagation. Strong coupling produces coherent collective modes; weak coupling maintains site independence. Topology affects sound: periodic boundaries create sustained resonances, open boundaries allow energy dissipation.

## 3.4 Quantum Fourier Transform (QFFT)

This model represents quantum fields in frequency space with mode entanglement.

*3.4.1 Mathematical Model.* Field in frequency space:

$$\tilde{\phi}(k,t) = \sum_i A_i e^{i(\omega_i t + \alpha_i)} + \lambda\tilde{\phi}^3(k,t) + \tilde{\eta}(k,t) \tag{10}$$

where $\tilde{\phi}(k,t)$ is the Fourier-transformed field, $A_i$ are spectral amplitudes, and $\tilde{\eta}(k,t)$ represents frequency-space fluctuations.

Mode entanglement via frequency modulation:

$$\omega_i(t) = \omega_i(1 + \epsilon\sin(\alpha_i t)) \tag{11}$$

where $\epsilon$ is entanglement strength.

*3.4.2 Parameters.* Base Frequency, State Type, Squeeze Parameter, Entanglement, Evolution Rate, Lambda, and Quantum Noise.

*3.4.3 Sonic Characteristics.* Produces spectrally rich, evolving textures. Entanglement creates frequency modulations and beating; evolution rate controls temporal change. Squeezed states create formant-like spectral shapes.

## 3.5 Path Integral Synthesis

Inspired by Feynman's path integral formulation, this model sums over all possible evolutionary paths weighted by action.

*3.5.1 Mathematical Model.* Path integral formulation:

$$\phi(x,t) = \int \mathcal{D}\phi \, e^{iS[\phi]/\hbar} \tag{12}$$

where $S[\phi]$ is the action functional.

Sound synthesis approximation:

$$\phi(t) = \sum_{i=1}^{H} \sum_{p=1}^{P} A_{ip} \sin\left(\frac{\omega_p}{d}(1 + \delta\omega_i)t + \phi_i(t)\right) \tag{13}$$

where $H$ is harmonics, $P$ is paths, $d$ is path density, and $A_{ip}$ are action-weighted amplitudes.

*3.5.2 Parameters.* Path Frequency, Number of Paths, Path Density, Action Factor, Evolution Rate, $\hbar$ Value, Quantum Noise, and Vacuum Energy.

*3.5.3 Sonic Characteristics.* Creates complex, evolving timbres with characteristic "quantum" sound. Lower $\hbar$ produces deterministic sounds; higher values create chaotic, probabilistic timbres. Path number and density control spectral richness.

# 4 Implementation Details

## 4.1 SuperCollider Implementation

Each quantum field model is implemented as a SynthDef with: oscillator banks (arrays representing field modes), nonlinear processing (waveshaping for $\phi^3$ self-interactions), noise generators (white noise for quantum fluctuations), state management (quantum state logic), and parameter controls (real-time input).

## 4.2 Graphical User Interface

The GUI includes: model selection dropdown, dynamic control panels updating per model, parameter sliders with numeric displays, Play/Stop/Reset buttons, and sectioned layouts for parameter grouping. Implemented using SuperCollider's standard GUI components.

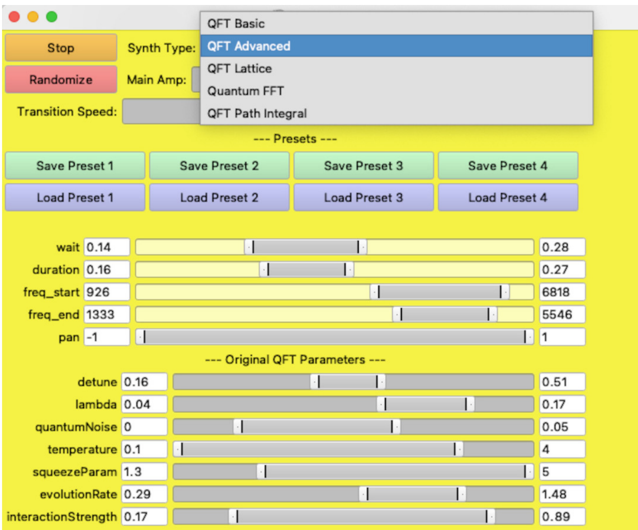


**Figure 1: SuperCollider graphical user interface for the QFT Sound Synthesis Framework. The interface features a model selection dropdown (showing QFT Basic, QFT Advanced, QFT Lattice, Quantum FFT, and QFT Path Integral options).**

## 4.3 Real-time Parameter Mapping

Abstract quantum parameters map to synthesis parameters via: exponential mappings (frequency, squeeze parameters), linear mappings (interaction strengths, amplitudes), and discrete mappings (state selection, integers).

# 5 Applications

## 5.1 Musical Applications

The framework enables: novel quantum-based sound design, exploration of complex timbral spaces through physically meaningful parameters, generation of evolving organic textures with quantum behaviors, and music embodying quantum concepts (uncertainty, superposition, entanglement).

## 5.2 Educational Applications

Serves as an educational tool providing: immediate auditory feedback for quantum concepts, tangible representations of abstract theory, interactive parameter space exploration, and demonstration of relationships between quantum phenomena and wave behavior.

# 6 Future Directions

Potential extensions include: gauge field implementation, fermion fields and spin representation, quantum computing integration, 3D spatial audio for field representation, and machine learning tools for parameter space navigation.

# 7 Conclusion

The QFT Sound Synthesis Framework bridges quantum field theory's abstract mathematics with experiential sound and music. By translating quantum concepts into audible form, it provides both educational insight and creative possibilities. This cross-disciplinary approach yields novel tools benefiting science and art, opening new avenues for understanding and expression.

# Acknowledgments

The author acknowledges the support by Goethe Institute and Raman Research Institute.

# References

[1] Michael E. Peskin and Daniel V. Schroeder. 1995. *An Introduction to Quantum Field Theory*. Westview Press, Boulder, CO.
[2] Steven Weinberg. 1995. *The Quantum Theory of Fields, Volume 1: Foundations*. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9781139644167
[3] Curtis Roads. 2004. *Microsound*. MIT Press, Cambridge, MA.
[4] Scott Wilson, David Cottle, and Nick Collins. 2011. *The SuperCollider Book*. MIT Press, Cambridge, MA.

Received 20 February 2025; revised 15 March 2025; accepted 5 April 2025