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QUANTUM-INSPIRED REVERBERATION USING RAY TRACING METHOD

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ABSTRACT

Reverberation—the persistence of sound in a cavity due to reflections—is a frequency-dependent phenomenon central to spatial audio and acoustic design. In this work, we draw an analogy with cavity quantum electrodynamics (CQED), where light waves confined in cavities interact with matter through distance-dependent dipolar couplings mediated by virtual photons. Inspired by this framework, we propose a novel method for simulating acoustic reverberation using a ray-based model [1] inspired by quantum dipolar interactions [2]. Traditional ray-tracing models often rely on fixed or empirical reflection coefficients, which do not capture the spatially varying interaction strengths characteristic of CQED. To address this, we introduce quantum-inspired interaction models translated into distance-dependent gain functions. These functions are embedded into a 2D geometric ray tracing engine to compute synthetic impulse responses in a rectangular cavity. A comparison of the impulse responses across four interaction models demonstrates that stronger distance dependence results in sharper attenuation of late reflections. This approach offers a new perspective for physically grounded, tunable reverberation modeling with potential applications in sound synthesis and cross-domain analog simulations.

Keywords: *Reverberation Modeling, Cavity Quantum Electrodynamics (CQED), Ray Tracing, Dipolar Interactions, Convolution Reverb.*

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1. INTRODUCTION

Ray tracing is a well-established technique in classical acoustics, used to approximate the propagation of sound through reflection in enclosed environments [1]. By modeling sound as discrete rays, this method is particularly effective at high frequencies, where the acoustic wavelength is small compared to the size of the room. It allows for efficient simulation of energy transport in architectural acoustics, virtual environments, and spatial audio rendering [3]. Traditionally, these models employ fixed or empirically derived reflection coefficients at boundaries, which limits their ability to incorporate distance-dependent interaction analogies inspired by CQED.

In contrast, CQED offers a framework where emitter-boundary and emitter-emitter interactions are mediated by vacuum field fluctuations and quantized electromagnetic interactions. These interactions occur via the exchange of virtual photons and are highly dependent on geometry and distance [4]. Notably, such couplings follow distance-dependent power laws and are central to phenomena such as the van der Waals and Casimir–Polder effects [2].

Motivated by this parallel, we propose an acoustic analogy to these dipolar interactions by embedding distance-dependent gain functions into a classical ray-tracing framework. This approach allows us to explore the impact of quantum-inspired interaction models on reverberation characteristics. Specifically, we:

- Implement a classical 2D ray tracing engine.
- Replace fixed reflection coefficients with synthetic,

distance-dependent interaction models.

- Simulate impulse responses using quantum-inspired interaction functions.
- Convolve the impulse response with real audio signals to demonstrate practical audio processing potential.

Section 2 provides background on quantum dipolar interaction models. Section 3 describes the ray tracing method and the construction of impulse responses using distance-dependent gains. Section 4 presents and analyzes the simulation results. Section 5 discusses implications and outlines future directions, and Section 6 concludes the paper.

2. BACKGROUND: QUANTUM DIPOLAR INTERACTIONS

2.1 Dipole-dipole Interaction

The dipole–dipole interaction potential V_{dd} describes the coupling between two electric dipoles—either between two atoms or between an atom and its image dipole, as may occur near a reflective medium. These interactions extend over larger distances and exhibit anisotropic dependence [5]. The total Hamiltonian of the system is expressed as:

$$H = H_0 + V_{\text{dd}}, \tag{1}$$

where H_0 represents the Hamiltonian of two non-interacting atoms. In the near-field regime, where the dipole separation is much smaller than the wavelength of the exchanged radiation ($r \ll \lambda$), this interaction strength decays as:

$$V_{\text{dd}}(r) \propto \frac{1}{r^3}. \tag{2}$$

Although the full interaction depends on the relative orientation of the dipoles and the vector connecting them, we restrict our model to an isotropic scalar version of the interaction. This simplification retains the essential long-range character of the potential while making it suitable for acoustic analogy and computational implementation.

In the context of CQED, these interactions arise due to the exchange of virtual photons between dipolar emitters, and they are strongly influenced by the presence and geometry of surrounding boundaries.

2.2 Van der Waals Interaction

The van der Waals (vdW) interaction emerges from quantum fluctuations of the atomic dipoles and the electromagnetic field [2]. It can be understood as second-order correction to the system's energy, obtained from time-independent perturbation theory applied to this interaction potential V_{dd} in the total Hamiltonian $H = H_0 + V_{\text{dd}}$, as introduced in Eq. (1).. The energy shift of the ground state is given by:

$$\Delta E^{(2)} = \sum_{n \neq 0} \frac{|\langle n|V_{\text{dd}}|0\rangle|^2}{E_0 - E_n}, \tag{3}$$

where $|0\rangle$ is the unperturbed ground state, $|n\rangle$ are excited states of H_0, and E_0, E_n their respective energies.

In isotropic cases, vdW forces are typically attractive, though their sign can vary in anisotropic or excited-state configurations [6]. The interaction follows two regimes:

- Near field or non-retarded regime ($r \ll \lambda$): $V_{\text{vdW}}(r) \propto \frac{1}{r^6}$
- Far field or retarded regime ($r \gg \lambda$): $V_{\text{vdW}}(r) \propto \frac{1}{r^7}$

The transition between regimes reflects the role of retardation—i.e., the time delay in the interaction due to the finite velocity of the wave.

2.3 Casimir-Polder Interaction

The Casimir–Polder (CP) interaction can be viewed as the retarded extension of the van der Waals interaction [2], applicable between a neutral polarizable atom and a macroscopic dielectric body mediated by vacuum-field fluctuations [7]. It also exhibits two distance regimes:

- Near field: $V_{CP}(r) \propto \frac{1}{r^4}$
- Far field: $V_{CP}(r) \propto \frac{1}{r^7}$

These interactions are particularly suited for describing atom–surface coupling in cavity settings, where the presence of boundaries modifies the vacuum field and leads to a near field r^{-4} scaling, in contrast to the r^{-6} behavior of atomic van der Waals interactions.

3. MODELING FRAMEWORK

We simulate an acoustic cavity as a 2D rectangular domain with an omnidirectional source. Rays are randomly launched across all directions, and their paths are traced through multiple reflections. At each interaction with the boundary, we apply a synthetic interaction function that modulates the amplitude of the ray.

3.1 Ray Tracing Principles

Each ray is a direction vector $\vec{v}$ emitted from a source position. When a ray encounters a wall, its specular reflection direction $\vec{v}'$ is computed following the geometric law in Eq. (4):

$$\vec{v}' = \vec{v} - 2(\vec{v} \cdot \vec{n})\vec{n}, \tag{4}$$

where $\vec{n}$ is the unit normal vector of the wall at the point of incidence. This formula ensures that the angle of incidence equals the angle of reflection, relative to the wall's surface normal. After each reflection, the ray travels a distance r_i, contributing a delay $\tau_i = r_i/c$, where c is the velocity of the wave.

3.2 Quantum-Inspired Interaction Models

Instead of using fixed attenuation for ray reflections, we introduce interaction-based gain functions that decay with propagation distance. These functions take the general form:

$$G(r) = \frac{1}{r^n + \epsilon}, \tag{5}$$

where ϵ is a small regularizing constant to avoid divergence as $r \to 0$, and n characterizes the type of interaction. In our simulations, we consider the following values of n:

- $n = 3$: dipole–dipole interaction (near-field), corresponding to the $1/r^3$ dependence shown in Eq. (2)
- $n = 4$: Casimir–Polder interaction (near field, atom–surface)
- $n = 6$: van der Waals interaction (near field, atom–atom)
- $n = 7$: Casimir–Polder (far field) interaction (or retarded van der Waals interaction)

3.3 Impulse Response Construction

Physically, the impulse response $h(t)$ describes how an acoustic system reacts over time to a brief, idealized input at the source location. It encodes the arrival times and amplitudes of sound energy reaching the receiver after multiple reflections within the cavity. The impulse response is constructed by accumulating the contributions of individual ray paths as time-delayed impulses modulated by the gain function $G(r)$, as shown in Eq. (6):

$$h(t) = \sum_i G(r_i) \cdot \delta(t - \tau_i) \tag{6}$$

This impulse response is then used in convolution with audio signals to simulate distance-sensitive reverberation.

4. RESULTS

We evaluate the effect of different interaction models by simulating a 5m×5m rectangular room with a centrally placed sound source. This configuration resembles small to medium-sized recording spaces. While dipolar interactions in CQED occur at nanoscales (1–1000nm), these scales are not directly transferable to acoustics due to the much lower speed of sound ($c = 343$ m/s). Applying dipole-like decay at such scales would yield unrealistically fast attenuation. Instead, we simulate a realistic acoustic cavity to preserve perceptual relevance.

A total of 10,000 rays are launched uniformly in all directions to ensure adequate spatial sampling of the acoustic field. Each ray is allowed up to 20 reflections to capture both early and late reflections contributing to the overall reverberation profile. Each ray's contribution is weighted by a distance-dependent gain corresponding to one of the four interaction models. The resulting impulse responses are shown in Fig. 1.

The shape of each impulse response reveals how interaction strength influences energy decay:

- Panel (a) shows a dense cluster of early reflections with relatively uniform amplitude up to approximately 0.2 seconds. This slower decay reflects the relatively long-range nature of the $1/r^3$ interaction (Eq. (2)), which allows more distant reflections to contribute energy over time.
- Panel (b) produces a slightly faster decay profile. Amplitudes drop more rapidly, but longer reflections remain perceptible up to around 0.25 seconds. This suggests a moderate suppression of energy at extended distances.
- Panels (c) and (d) exhibit steep early decay. Most energy is concentrated in the first 0.1 seconds, and late reflections are strongly attenuated, with panel (d) showing the sharpest drop.

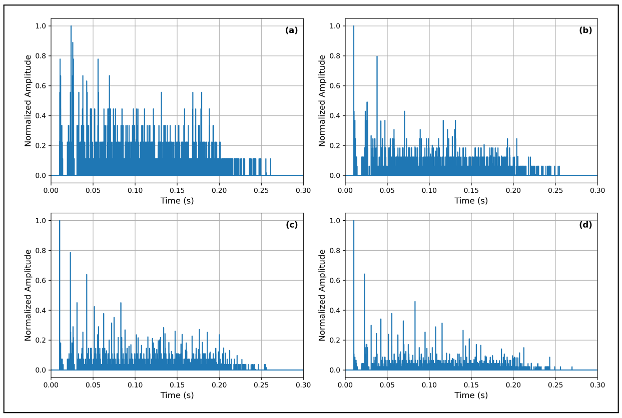

Figure 1. Impulse responses generated using four different quantum-inspired interaction models: (a) dipole-dipole interaction (near-field) $1/(r^3 + \varepsilon)$, (b) Casimir–Polder (near field) $1/(r^4 + \varepsilon)$, (c) van der Waals (near field) $1/(r^6 + \varepsilon)$, (d) Casimir–Polder (far field) or retarded van der Waals $1/(r^7 + \varepsilon)$.

These results confirm that increasing the power-law exponent in the gain model enhances the attenuation of late reflections. This offers a tunable framework for shaping reverberation decay using physically inspired models.

5. DISCUSSION AND FUTURE WORK

This method provides a physically interpretable approach to reverberation modeling by introducing distance-dependent interaction functions inspired by cavity quantum electrodynamics into acoustic ray tracing. Unlike traditional models with constant reflection coefficients, this framework allows for tunable, spatially sensitive energy decay. Future work could explore more complex 2D or 3D geometries, incorporate directional sound emission, and refine the gain functions to better reflect underlying quantum interactions. Real-time implementations with user-controlled dry/wet convolution mixing would also expand the method's utility in creative and interactive audio applications.

6. CONCLUSION

We have presented a method for incorporating quantum-inspired, distance-dependent interaction models into acoustic ray tracing. This framework allows for the generation of tunable impulse responses that reflect different physical assumptions about wave–boundary interactions. While grounded in an acoustic simulation context, the approach draws from cavity quantum electrodynamics and may offer new tools for reverb design. Future work may extend the method to more complex geometries, directional emission models, and real-time applications.

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