

Quantum Interference as Audio Waveforms

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Abstract

This paper presents a methodology for transducing audio waveforms directly from quantum circuit execution, using the probabilistic measurement outcomes of that execution to constitute the waveform directly.

Eight distinct topologies each produce a circuit of eight correlated qubits whose measured expectation values become audio waveforms, with the pattern of entanglement determining the amplitude and timbral relationships. Each topology consists of a four-layer circuit architecture engaging superposition, entanglement, rotation, and measurement. Specific transformations in the frequency, temporal, and amplitude domains are required to render the resulting waveforms audible.

The methodology culminates in the generation of eight audio samples that expose the microstructures of the raw quantum computationally derived data. They constitute the content of *The Infinite and the Infinitesimal*, a composition generated from this methodology.

Each circuit execution on quantum hardware was preceded by simulation to test and validate it before consuming hardware cycles. Comparisons between simulated and hardware-derived waveforms reveal how the interference patterns differ due to hardware noise. In this process, decoherence directly perturbs the acoustic

waveform and is a timbral and rhythmic characteristic of the hardware. This paper argues that this direct sensitivity to hardware noise is a defining feature of the transduction-based methodology.

Keywords: Quantum Computing, Quantum Computer Music, Sound Synthesis, Quantum Computational Creativity, Computer Music

Introduction

Figure 1 demonstrates a correspondence between the diagrams of quantum computational circuit execution results and the diagrams of audio waveforms. Several questions naturally arise from this observation: Can quantum waveforms be music? What would that music sound like and would it be recognizable as music? Is it possible for the design of quantum computational circuits to become sound synthesis and music composition? It is the direct *transduction* of quantum waveforms into sound that is the focus of the research delineated in this paper.

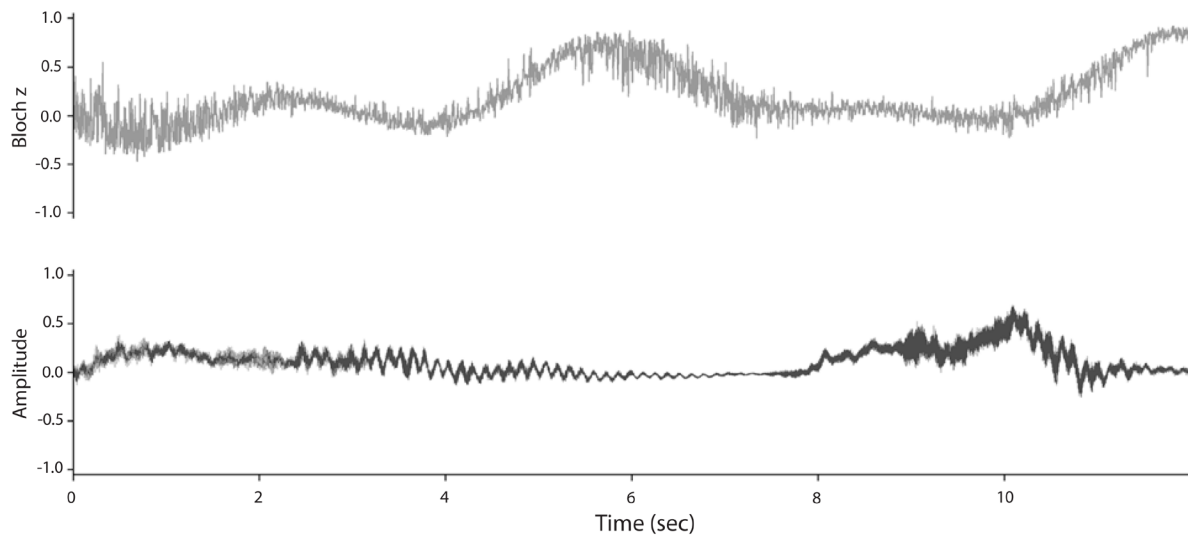


Figure 1. The visual correspondence between a quantum hardware execution trajectory (top) and the rendered audio of the resulting composition (bottom) that motivates this study.

Quantum computation in general requires a fundamental shift from a deterministic to a probabilistic perspective. Quantum circuit execution establishes and constrains the interactions of quantum particles, known as qubits, held within the extremely isolated environment of a quantum processor. It is here that what Einstein privately described as "spooky action at a distance" (Born 1971) can be indirectly observed, arising from the non-local correlation first formalized in the Einstein-Podolsky-Rosen paradox (Einstein, Podolsky, and Rosen 1935). The measurement problem in quantum physics involves the fact that when we measure the state of a quantum wavefunction, it collapses. We can, however, infer the pre-collapsed state of the quantum wavefunction based upon probabilities. This is a fundamental shift from classical computation, in which a bit is always in one state or another, 1 or 0. In quantum physics, a *qubit* exists in a *superposition*, a combination of the $|0\rangle$ and $|1\rangle$ states simultaneously, until measured, which is quite counter-intuitive. It is posited here that a perceptual shift from deterministic to probabilistic perspectives potentially offers access to novel creative approaches.

Computer music has long drawn on processes external to more conventional compositional practice to generate sonic material (Roads 1996). Early algorithmic, stochastic, granular, and spectral techniques have expanded the scope of that which constitutes a compositional unit (Roads 2001). Indeterminacy is often an aspect of this lineage. Cage's use of chance operations (Cage 1961), and the broader tradition of generative composition that followed, deliberately relinquished control over outcomes so that material could emerge outside the composer's direct intention. Further, Stephen Wolfram has shown that extraordinary complexity can emerge from the extensive reiteration of simple deterministic rules (Wolfram 2002). What these approaches share is that the composer authors the constraint. A tendency mask, a chance operation, or an iterated rule yields values its author did not foresee, but the range of what it can yield is generally understood.

The methodology presented here extends that lineage to another order of indeterminacy. A quantum circuit is specified by its entanglement topology, its gates, and its parameter sweep, and the compositional act is comprised of those specifications. What follows from it is not yet predictable in the way a tendency mask's range is predictable. The corresponding relationship ranges between entanglement topologies and auditory outcomes is not currently obvious, and the eight schemas presented here are an attempt to begin moving in that direction. Establishing these relationships renders the methodologies involved with circuit design and execution viable in the areas of sound design and composition.

Quantum computing applications in music have been explored through various approaches. Miranda's foundational work established frameworks for quantum music composition, including algorithmic methods and quantum-inspired techniques (Miranda 2017, 2022, 2025), and a recent survey maps the emerging field (Miranda 2024). A growing body of work at venues such as the International Symposium on Quantum Computing and Musical Creativity has explored related approaches, including quantum quasi-random number generation for stochastic composition and variational quantum circuits for sound synthesis optimization (Hamido and Itaboraí 2023).

Sonification, broadly construed, encompasses several related techniques under the umbrella of auditory display (Rhoades 2013). Here I refer specifically to sonification as *Parameter Mapping Sonification*, in which acoustic attributes are obtained through a mapping from data attribute values (Hermann, Hunt, and Neuhoff 2011). This mapping involves an interpretive function that translates data into sound. The earlier compositions in this project were built from that perspective. The methodologies presented in this paper depart from that model. Rather than mapping quantum measurement data to acoustic parameters through chosen

functions, the audio waveform is transduced directly from the quantum measurement itself, with no interpretive function between them.

This paper elucidates these premises in the following order. The Theoretical Foundations section provides a self-contained introduction to the relevant concepts in quantum computing. The Methodology section describes the approach as parameterized circuit architectures in which entanglement topology functions as a compositional parameter. The Circuit Topology section details eight specific configurations, chosen as functional and illustrative instances of an open-ended design space. The Transducing Measurement to Audio section addresses implementation of these circuits with sound synthesis as the target. The Compositional Results section introduces a quantum computationally derived musical composition. Finally, the Conclusions section discusses the results of this methodology and examines open questions.

Theoretical Foundations

For readers unfamiliar with the basics of quantum mechanics as is pertinent to quantum computing, this section is intended as a primer. Each of the components of a quantum circuit discussed here determine its topology. Here I present a simplistic topology for illustrative purposes and the gates discussed here are rudimentary in that the number of available gates is quite large (IBM 2026).

Quantum State Representation

In classical computing a bit is the basic computational unit. Its state is always equal to 1 or 0. Conversely, a qubit, the basic quantum computational unit, exists in superposition as a linear combination of basis states until measurement collapses it to a discrete value. For a single qubit, the state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ represents a probability amplitude distribution across basis states, where $|\alpha|^2 + |\beta|^2 = 1$ (Nielsen

and Chuang 2010). The evolution of these amplitudes through quantum gates creates interference patterns, which are central to this paper's methodology.

For an 8-qubit system, the state space encompasses $2^8 = 256$ possible measurement outcomes. Each quantum state is fully described by 256 complex probability amplitudes, forming a point in a 256-dimensional complex vector space known as the *Hilbert space* (Nielsen and Chuang 2010). As the quantum circuit executes, this point traces a trajectory through Hilbert space, and the measurement statistics at each point encode the interference relationships between qubits.

Entanglement

Quantum *entanglement* occurs when the states of two or more qubits become correlated in ways that cannot be described independently. Measuring one qubit instantaneously affects the probability distribution of the other (Bell 1964; Horodecki et al. 2009). This non-local correlation is another fundamental mechanism in this paper's methodology. Different entanglement topologies produce different correlation structures, which translate directly into the amplitude relationships between the resulting audio waveforms.

Interference

Quantum *interference* arises when the probability amplitudes associated with different quantum states combine, producing constructive or destructive effects depending on their relative phases (Feynman 1985). In a parameterized quantum circuit, as a rotation angle θ sweeps through its range, the interference between entangled qubits creates smoothly varying probability distributions. It is this continuous variation, measured repeatedly and aggregated across many shots, that produces the continuous waveforms at the center of this paper's methodology.

Decoherence

Decoherence is the loss of a qubit's well-defined superposition or entangled state, through its undesirable interaction with its surrounding environment (Nielsen and Chuang 2010). A qubit is never perfectly isolated. Even in a controlled laboratory system, it is coupled, however weakly, to its environment, which consists of nearby electromagnetic fields, thermal vibrations in the surrounding material, control electronics, and so on. These interactions leak information about the qubit's state out into the environment, and as they do, the qubit's state loses the precise phase relationships that define a coherent superposition. Geometrically, a qubit's state can be pictured as a vector within a unit sphere known as the *Bloch sphere*, on which the poles represent the two definite outcomes and all intermediate points represent superpositions (Nielsen and Chuang 2010). Decoherence manifests as that vector's length shrinking and its tip moving from the sphere's surface toward its interior. The radius r is therefore a measure of *purity*, the *coherence* remaining in the state.

Decoherence is not the same as gate error, which is an imperfection in a specific operation, such as a rotation landing at a slightly wrong angle. Decoherence is ongoing, happening continuously across time even when no gate is being applied, simply because the qubit exists and is coupled to its environment. Ultimately, the propensity for decoherence within a given hardware environment could be thought of as its signature and, in this methodology, it directly affects the resultant timbre of a given circuit execution.

Reading a Quantum Circuit

Referencing the example circuit in Figure 2 (a reduced three-qubit example used here for clarity; the circuits in this study each use eight qubits), each horizontal line represents one qubit, labeled q_0 , q_1 , q_2 , down the left edge. Time moves left to right along each line.

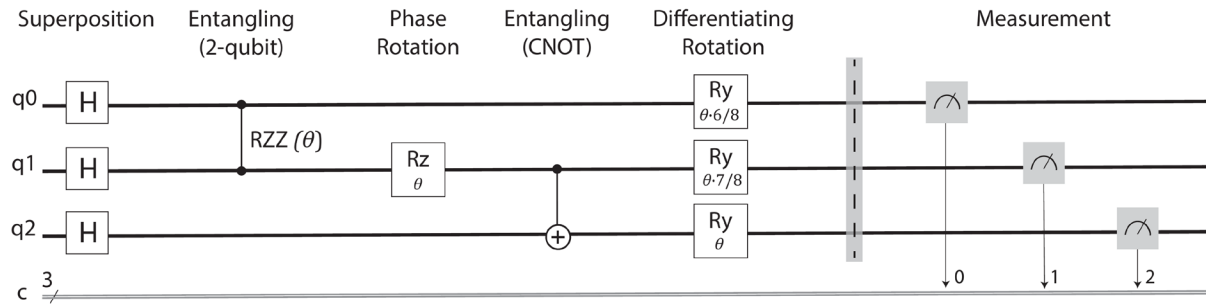


Figure 2. An example three-qubit circuit, annotated by stage, showing the gate, barrier, and measurement conventions used throughout the paper.

The boxes represent gates, which are operations performed on the qubits. In the example circuit, the H box is the Hadamard gate, which places a qubit into superposition. The Rz and Ry boxes are rotation gates, which tilt the qubit's state vector on the Bloch sphere by a specified angle. The small number or symbol below the gate name, such as θ or $\pi/4$, is the stipulation of that angle.

A vertical line connecting two qubit lines, with a solid dot on each end, represents a two-qubit gate, an operation that acts on both qubits and creates entanglement. In this diagram, the RZZ gate between q0 and q1 consists of the gate's name and angle beside it.

The line with a dot on one end and a circle containing a cross on the other is a specific and common two-qubit gate called CNOT (controlled-NOT), sometimes written CX. The solid dot marks the control qubit and the circled cross marks the target qubit. In plain terms, CNOT flips the state of the target qubit, but only if the control qubit is in a particular state. This conditional flip, applied to qubits already in superposition, is another way of creating entanglement.

The vertical gray bar is called a barrier. It is simply an organizational marker, telling the reader and the compiler that will execute the circuit that everything to the left of the bar is considered one phase of the circuit and everything to the right is

another. In this diagram, the barrier separates the gates that shape the qubits' quantum state from the measurement gates.

The boxes containing a small meter-like arc at the right-hand end of each qubit line represent measurements. This is the point at which each qubit's quantum state is read and converted into an ordinary classical bit, a plain 0 or 1. Measurement is a one-way step. Once a qubit has been measured, its superposition is gone, collapsed to whichever single outcome was read.

The single horizontal line at the bottom, labeled c , with a small diagonal slash and the number 3 beside it, represents the classical register, the classical computer memory that stores the results of measurement. The slash and number are a shorthand meaning "this single line represents three classical bits bundled together," one for each of the three qubits' measurement outcomes. The arrows from each measurement box down to this line show each qubit's result being written into its own bit of that classical memory.

Steps and shots, mentioned throughout this paper, refer to how a single circuit design is executed. A circuit like this one is built around an angle, θ , and is executed repeatedly across a whole range of θ values, from 0 up to 2π . Each distinct value of θ is one *step*. At each individual step, the entire circuit is executed many times. Since a single quantum measurement returns only one collapsed outcome, a single execution reveals nothing about the underlying probabilities. Each individual execution of the circuit at a given step is one *shot*. The circuits in this project execute 1,024 shots per step, and the measured outcomes across all those shots are averaged to reconstruct the qubit's expectation value, an exact property of the state that any individual shot can only sample, at each step. This measurement is the average projection onto the Bloch sphere's z axis and is a number between -1 and +1.

Methodology

Hardware validation was conducted using Quantum Inspire's Tuna-9 processor, a 9-qubit transmon system, in which the qubits are arranged in a diamond configuration; each schema in this study uses eight of these nine qubits. All eight schemas were executed, totaling 19,200 quantum circuits (2,400 parameter steps $\times$ 8 schemas), with 1,024 shots per circuit. Execution was conducted across multiple sessions over several days, accommodating platform calibration cycles and intermittent connection errors, with data saved incrementally in batches as comma-separated values (CSV) files.

Circuit construction and simulated pre-hardware testing were carried out in Python using an open-source quantum computing software development kit (Qiskit), with a noise-free state-vector simulator used during development. Hardware execution was carried out on a 9-qubit transmon backend (Quantum Inspire Tuna-9). The methods described here are not specific to these tools and can be implemented with any comparable circuit-construction framework and hardware provider.

As previously discussed, the circuit topologies for this research and creative praxis consist of a four-layer structure with θ sweeps and shots. These are relatively simple topologies drawn from an immense space of possible circuit topologies, one that grows exponentially with the number of qubits involved.

Just as a composer working in conventional practice might choose between homophonic and polyphonic textures, the composer working in this methodology selects among entanglement configurations that encode distinct correlation relationships between voices. Central to this methodology is the treatment of entanglement topology as a determinant of acoustic and timbral character, and through that, as a compositional parameter. Within each of the eight schemas discussed in the following section, qubit 0 generally functions as a *fundamental*,

analogous to a fundamental frequency in acoustic timbre, while qubits 1 through 7 function as ancillaries, analogous to partials. The strength of entanglement between *ancillary* qubits and the fundamental qubit determines that ancillary's relative amplitude in the resulting waveform. Stronger entanglement produces higher amplitude. The composite of all eight waveforms within a schema thus forms a timbral signature specific to that schema's topology.

Circuit Topology

The eight schemas presented here were chosen as functional, pedagogically varied instances of an open-ended design space. Any pattern of two-qubit entangling connections defines a distinct topology and these eight range from maximal uniform entanglement in the Greenberger-Horne-Zeilinger (GHZ) state through fully independent subgroups (Islands, Pairs) to graded and hierarchical structures (Gradient, Tree), giving a broad survey of how connectivity shapes the resulting waveforms.

For each schema, the circuit is described first, followed by a circuit diagram and a diagram of its measured waveform results. All eight circuits open with a Hadamard superposition layer and close with a measurement layer, and between them each carries an entangling layer and a differentiating Ry rotation layer that gives every qubit a distinct trajectory where entanglement alone would not. The form of those two middle layers varies by schema. Star, Chain, Pairs and GHZ apply an ascending rotation, $Ry(\theta \cdot (i+1)/8)$ on qubit i ; Gradient reverses it; Ring and Tree scale it harmonically, by qubit index and by tree depth respectively; and Islands mirrors a quarter series across its two groups. Chain, Pairs, GHZ and Islands additionally carry phase rotations within or after their entangling layers. Two measures recur in the results that follow. Shape retention is the Pearson correlation between a qubit's simulated and hardware trajectories across the parameter sweep,

reported per qubit as a signed correlation and summarized for each schema as the mean of those per-qubit values taken in absolute value; a schema value near one means that hardware execution preserved the simulated trajectories, a value near zero means that it did not, and a negative per-qubit value means the hardware trajectory inverted the simulated one. Spectral flatness is the ratio of the geometric mean to the arithmetic mean of a waveform's magnitude spectrum, with the DC component excluded, ranging from zero for a purely tonal signal to one for noise.

Schema 1: Star

All seven ancillary qubits entangle directly with qubit 0, and no ancillary entangles with any other, as shown in Figure 3. The coupling strength decreases as the qubit index rises, $RZZ(\theta \cdot (8-i)/8, 0, i)$ for i in 1 through 7. This hub-and-spoke connectivity gives qubit 0 degree seven and every ancillary degree one, so the ancillaries relate to one another only indirectly, through their shared connection to the hub.

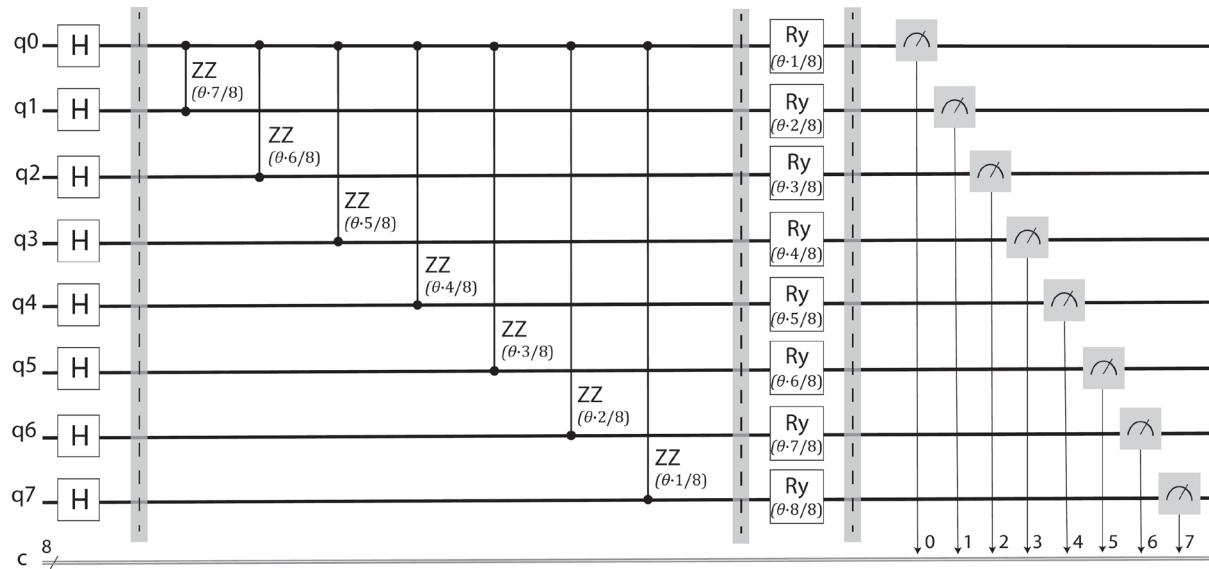


Figure 3. The Star schema circuit, in which every ancillary qubit entangles directly with hub qubit 0 at a coupling strength that decreases with qubit index.

Figure 4 shows one of the most complete transformations in the dataset. Hardware retains 0.13 of the simulated shape while holding amplitude near parity at 1.08 times simulation, so the trajectories are replaced rather than attenuated. The hub is the extreme case: its simulated trajectory is nearly flat, at the shot noise floor, while its hardware trajectory sweeps 3.6 times wider. Qubits 0 through 3 carry textural complexity over a recognizable arc, and qubits 4 through 7 hold a positive mean offset while still crossing zero throughout, dropping below it for 25 to 40 percent of each run. At a spectral flatness of 0.765 the resulting material sits well toward the noise end of the eight schemas.

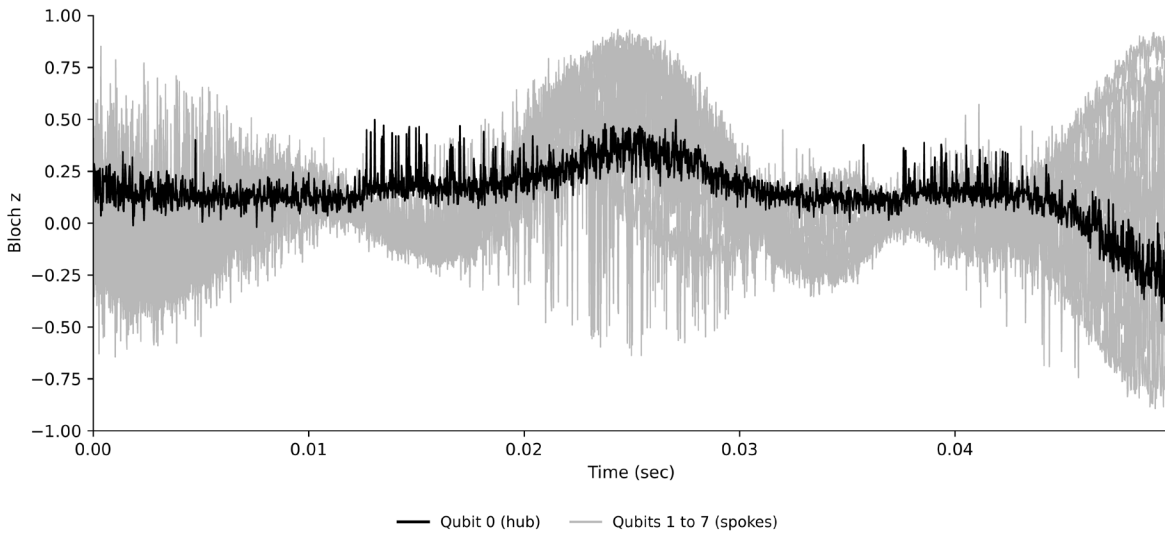


Figure 4. Hardware waveforms for the Star schema, the hub qubit 0 (black) holding a lower amplitude than the seven ancillary spokes (gray).

Schema 2: Chain

Sequential nearest-neighbor entanglement, $RZZ(\theta, i, i+1)$ for i in 0 through 6 at a single shared strength, shown in Figure 5, forms a linear propagation structure in which each qubit entangles only with its immediate neighbors. Each entangling gate is followed by a phase rotation on its target qubit, $Rz(\theta \cdot (i+1)/8)$ on qubit $i+1$, so that

phase accumulates along the chain. No connection spans more than one step, and the two endpoints, qubits 0 and 7, carry degree one where every interior qubit carries degree two.

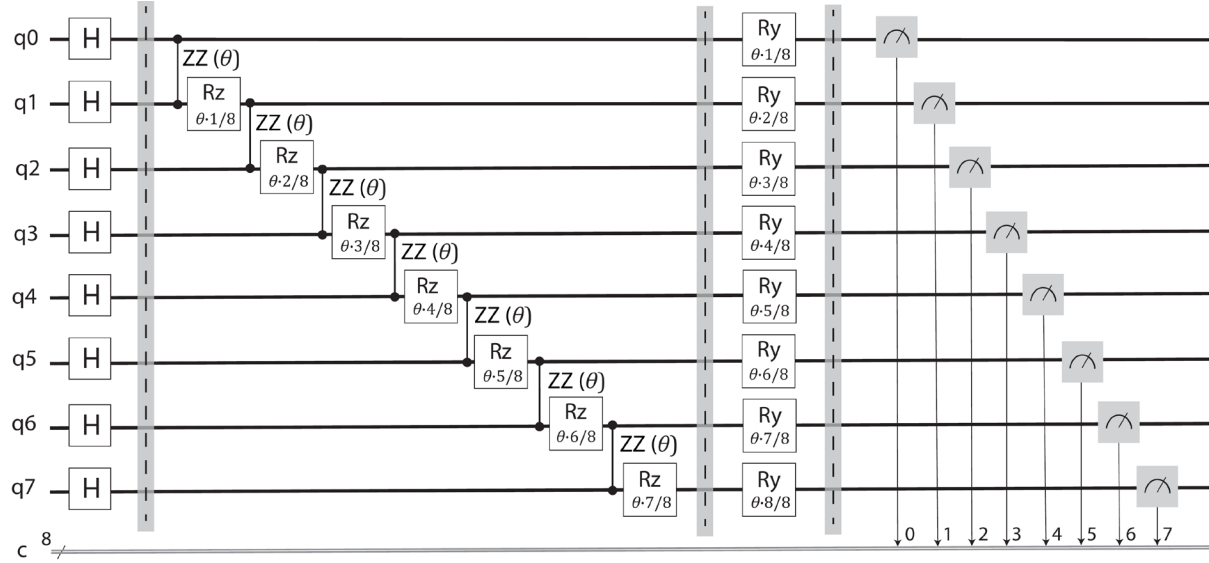


Figure 5. The Chain schema circuit, a sequence of nearest-neighbor entangling gates along which a phase rotation accumulates from qubit to qubit.

Figure 6 shows the highest shape retention of any schema, 0.59, with hardware amplitude slightly exceeding simulation at 1.18. Retention falls with distance from the root, from 0.96 at qubit 0 through 0.75, 0.63 and 0.39, to an inverted -0.87 at qubit 5, so position in the chain governs how much of the simulated trajectory survives execution. At the terminus a distinct periodicity emerges. Qubit 7 produces a coherent, near-tonal waveform in both conditions, but the two do not agree on its rate: simulation concentrates its energy in the first and third spectral components while hardware relocates it to the fourth, raising the perceived pitch of the rendered material substantially.

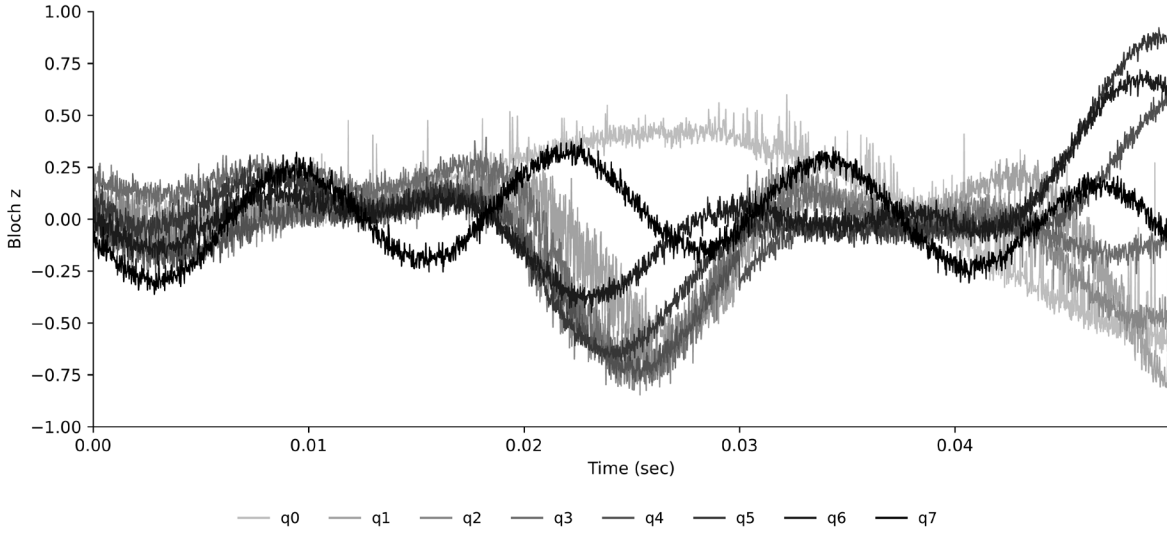


Figure 6. Hardware waveforms for the Chain schema, whose shape retention is the highest of the eight and whose terminus qubit 7 settles into a near-tonal periodicity.

Schema 3: Ring

The chain structure shown in Figure 7 adds one further connection, $RZZ(\theta, 7, 0)$, closing the sequence into a loop, with all eight entangling gates at a single shared strength and no intervening phase layer. Every qubit then has exactly two neighbors and none is structurally distinguished as an endpoint, making Ring the only degree-uniform topology among the eight. Its rotation layer is likewise distinct, scaling harmonically as $Ry(\theta/(i+1))$ rather than ascending.

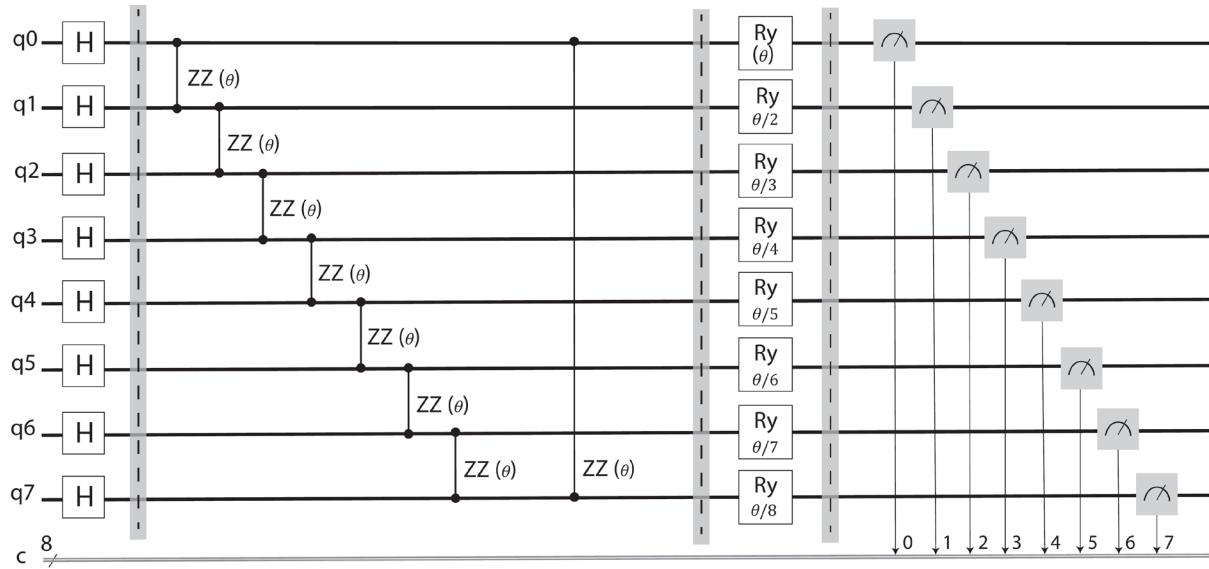


Figure 7. The Ring schema circuit, the chain closed into a loop so that every qubit has exactly two neighbors and none is a distinguished endpoint.

Figure 8 shows shape retention of 0.44 under amplitude compression to 0.87 of simulation. Retention is uneven rather than uniform, peaking at 0.85 for qubit 2 and inverting for qubits 5 through 7, so the loop does not protect its members equally. Ring nonetheless produces the strongest coupled-pair correlation of any schema under hardware, 0.673 in Table 1, which is what degree uniformity buys. Where Star's asymmetric hub produced outright transformation, Ring's closed topology yields timbral variation, the same underlying material voiced differently. One qubit, q1, showed an initial noise burst suggestive of a calibration artifact rather than a structural feature of the topology.

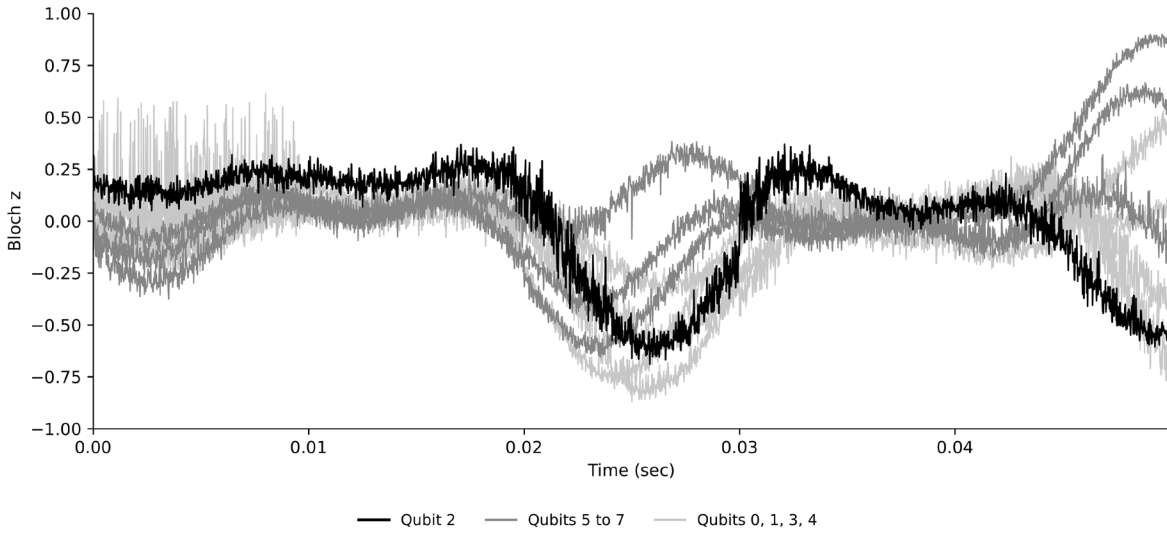


Figure 8. Hardware waveforms for the Ring schema, whose degree-uniform topology yields the strongest coupled-pair correlation of the eight schemas.

Schema 4: Pairs

Schema 4, diagrammed in Figure 9, consists of four two-qubit systems with no entangling connection between them: $RZZ(\theta, 0,1)$, $RZZ(\theta \cdot 5/4, 2,3)$, $RZZ(\theta \cdot 3/2, 4,5)$ and $RZZ(\theta \cdot 7/4, 6,7)$. Each pair then receives a controlled phase interaction, a CNOT followed by $Rz(\theta \cdot (k+4)/8)$ on the target and a second CNOT, for pair k in 0 through 3. The pairs are isolated from one another but not identical to one another, since both the entangling strength and the phase angle rise across the four. This is the most sparsely connected of the eight topologies.

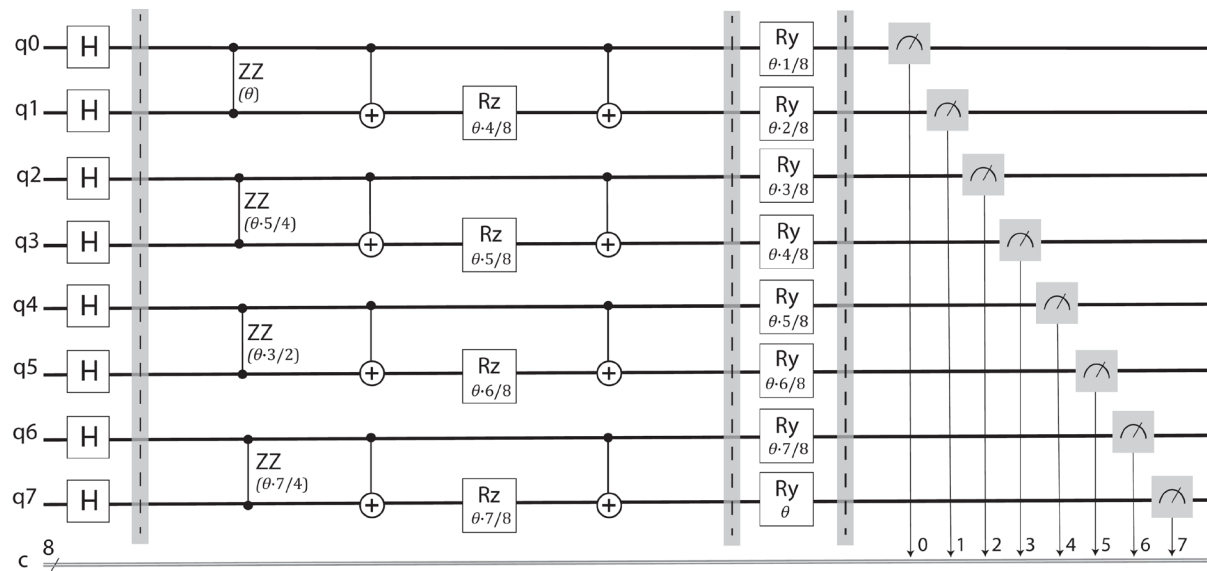


Figure 9. The Pairs schema circuit, four mutually isolated two-qubit systems entangled at rising strengths, each carrying a controlled phase interaction.

Figure 10 shows the most tonal material in the dataset, a spectral flatness of 0.535 against a range across schemas reaching 0.826, together with clean near-sinusoidal structure across all eight qubits. Hardware retains 0.46 of the simulated shape at 0.70 of its amplitude, but does so with polarity inverted: seven of the eight qubits correlate negatively with simulation, averaging -0.43. Within each pair the two qubits hold a consistent temporal offset, entanglement rendered as a canon between partner voices rather than as shared amplitude or shared noise character. The isolation between pairs is a property of the simulated circuit more than of its execution; under hardware the within-pair correlation advantage falls by roughly three quarters, as reported in Table 1.

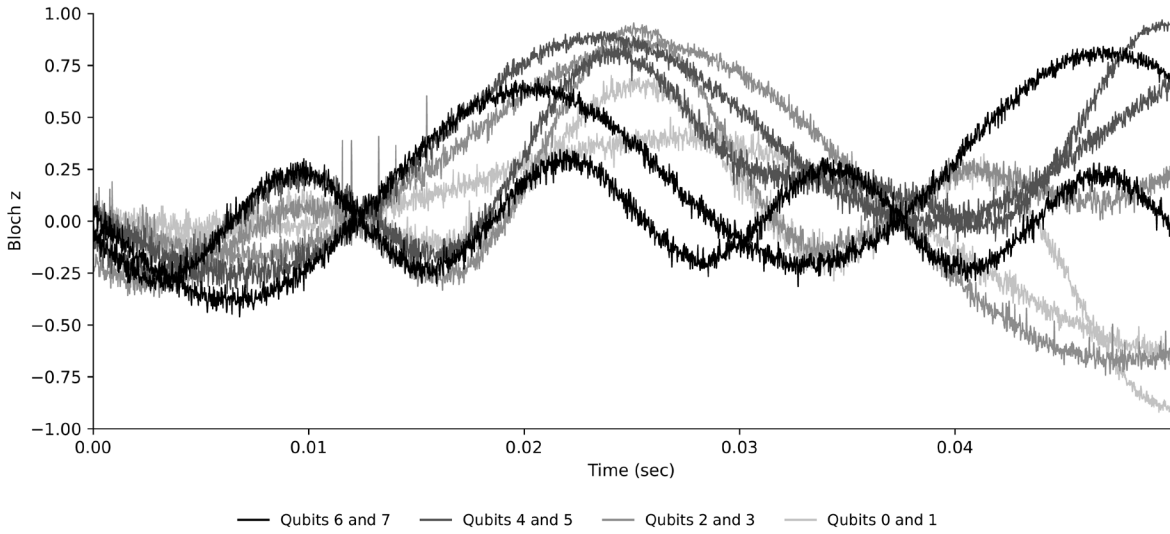


Figure 10. Hardware waveforms for the Pairs schema, the most tonal material of the eight, with partner qubits rendered as an offset canon.

Schema 5: Tree

Hierarchical binary branching from qubit 0, shown in Figure 11: $RZZ(\theta, 0,1)$ and $RZZ(\theta, 0,2)$ at full strength; $RZZ(\theta \cdot 0.7, 1,3)$, $RZZ(\theta \cdot 0.7, 1,4)$, $RZZ(\theta \cdot 0.7, 2,5)$ and $RZZ(\theta \cdot 0.7, 2,6)$ at a second tier; $RZZ(\theta \cdot 0.5, 3,7)$ at a third. Coupling strength decreases with tree depth, so qubits further from qubit 0 entangle more weakly than those nearer it, and the rotation layer follows the same hierarchy, $Ry(\theta/(d+1))$ for a qubit at depth d .

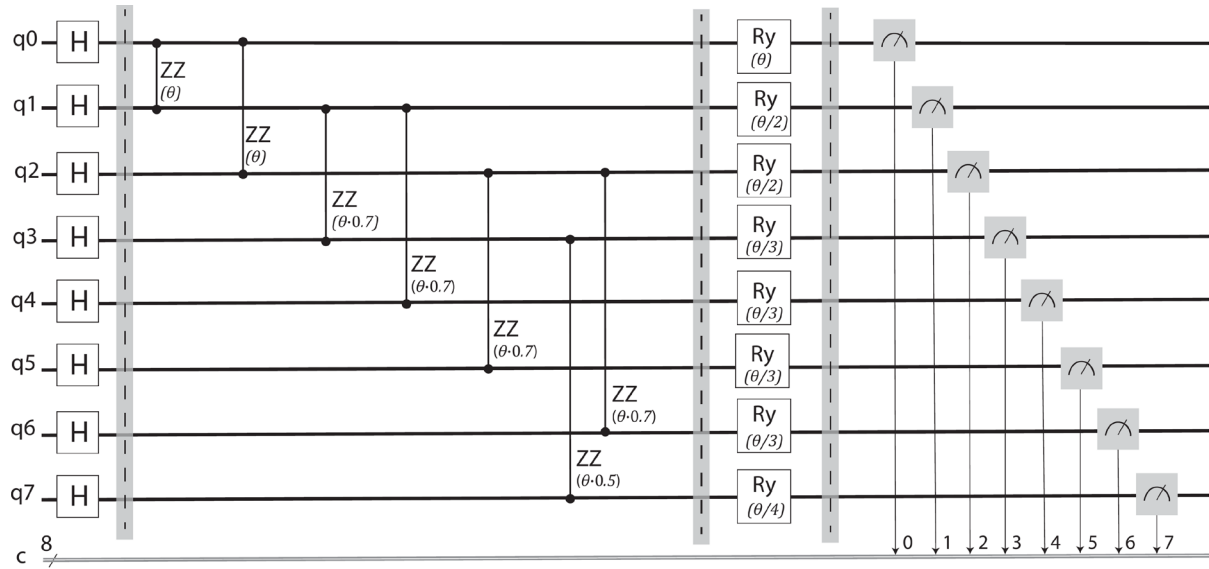


Figure 11. The Tree schema circuit, a hierarchical binary branching from qubit 0 whose coupling strength decreases with depth.

Figure 12 shows the strongest amplitude attenuation of any schema, hardware reaching only 0.54 of simulation, with shape retention of 0.31. Retention does not order by depth. The root is among the least preserved at -0.49 while the second-tier qubits 2 and 3 are the best preserved at 0.22 and 0.41, so the graded coupling that structures the circuit is not what governs which trajectories survive. Tree and Gradient both decay coupling strength with distance from the root, but where Gradient's decay yields a clear foreground and background, Tree's yields attenuation without a corresponding order.

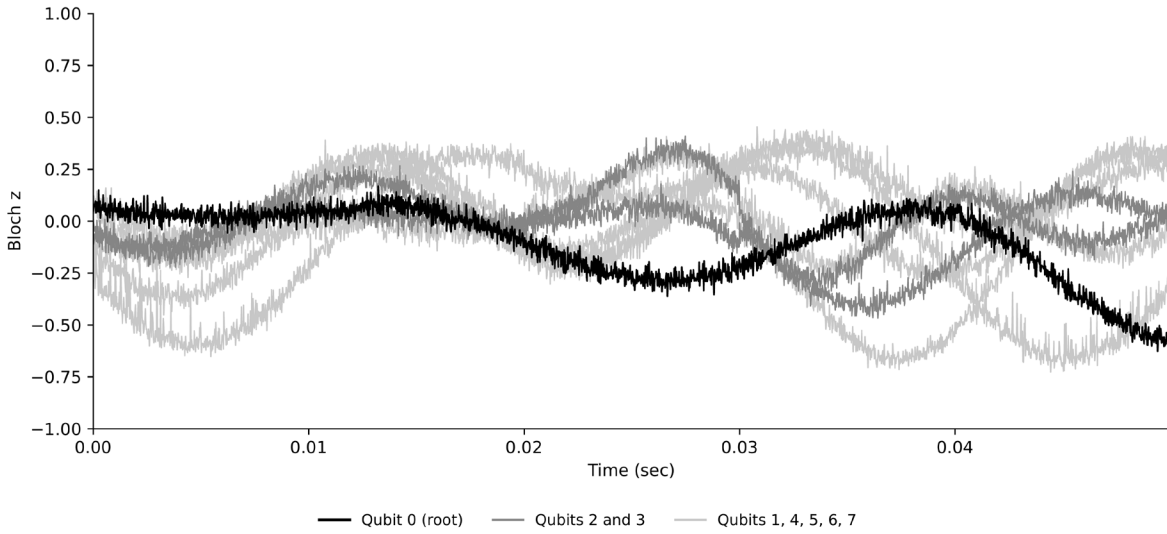


Figure 12. Hardware waveforms for the Tree schema, showing the strongest amplitude attenuation of the eight, with shape retention that does not order by depth.

Schema 6: GHZ

The GHZ construction (Greenberger, Horne, and Zeilinger 1989) in Figure 13 consists of a Hadamard gate on qubit 0 followed by a CNOT cascade, $CX(0,1)$, $CX(1,2)$, through $CX(6,7)$, placing all eight qubits into maximal entanglement. A uniform $R_z(\theta)$ phase rotation is then applied to every qubit, followed by a uniform $R_y(\theta/10)$ and a differentiating $R_y(\theta \cdot (i+1)/160)$ on qubit i . Those final rotations are two orders of magnitude smaller than any other schema's. Because the entanglement is both maximal and uniform, no qubit occupies a distinguished position and the circuit carries no structural asymmetry.

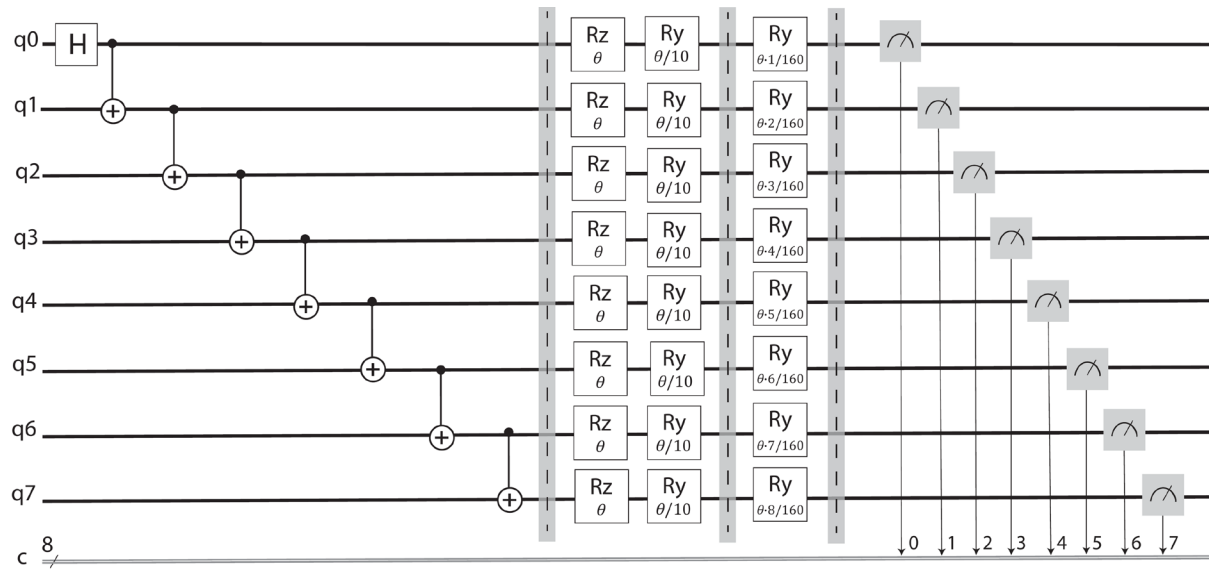


Figure 13. The Greenberger-Horne-Zeilinger (GHZ) schema circuit, a Hadamard gate followed by a CNOT cascade that places all eight qubits into maximal, uniform entanglement.

Figure 14 shows the extreme case. Shape retention is 0.007, two orders of magnitude below any other schema, meaning the simulated and hardware trajectories are effectively uncorrelated rather than merely divergent. Both are noise. Hardware amplitude exceeds simulation at 1.43, yet both remain within a narrow band roughly an order of magnitude smaller than the other schemas, and a spectral flatness of 0.826 makes this the noisiest material of the eight. The one systematic feature is a small DC offset that separates the qubits into two groups by degree rather than by sign: q_0 through q_3 average 0.042 against 0.015 for q_4 through q_7 , every qubit positive, in a schema whose entire range is roughly ± 0.15 . The grouping follows the direction of the CNOT cascade, though not monotonically. Where Star's single-point hub gave hardware noise a structural asymmetry to act on, GHZ's uniform maximal entanglement gives it none.

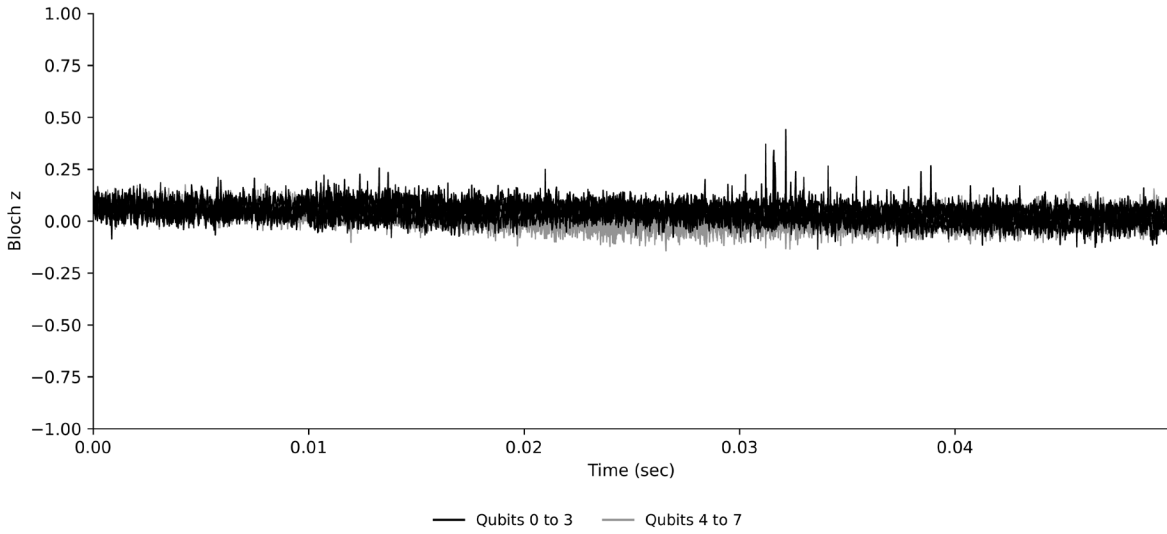


Figure 14. Hardware waveforms for the GHZ schema, a low-amplitude noise band in which qubits 0 to 3 sit slightly above qubits 4 to 7, the noisiest material of the eight.

Schema 7: Gradient

In the gradient topology every ancillary qubit entangles directly with qubit 0 at a coupling strength that decreases with qubit index, $RZZ(\theta \cdot (8-i)/8, 0, i)$ for i in 1 through 7, shown in Figure 15. Gradient shares both the connectivity and the decaying coupling profile of Star, and differs from it only in the direction of the rotation layer: where Star's rotations rise with qubit index, Gradient's fall, $Ry(\theta \cdot (8-i)/8)$, so that a single decay factor governs both a qubit's entangling strength and its own rotation.

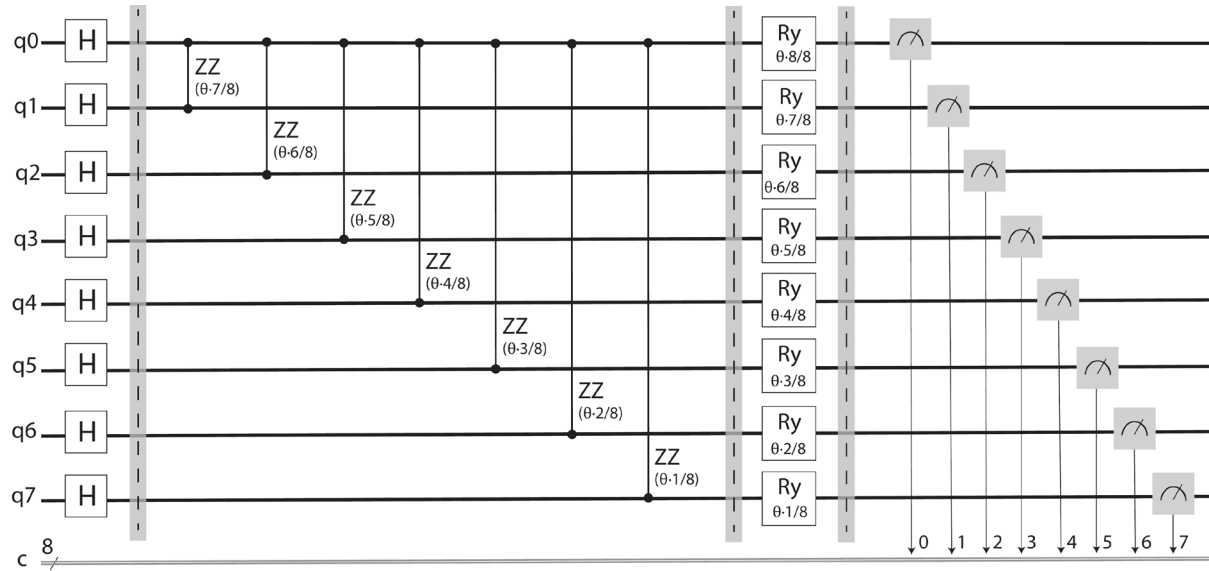


Figure 15. The Gradient schema circuit, sharing Star's hub connectivity but with both coupling strength and rotation decaying together across qubit index.

Figure 16 shows hardware amplifying that decay. Shape retention is 0.10, the second lowest of the eight, and amplitude falls to 0.70 of simulation. Qubit 0 shows a shallow arc. Qubits 1 through 4, the most strongly coupled ancillaries, produce the richest gestural behavior in the entire dataset, with large irregular excursions reaching ± 0.8 . Qubit 5 marks a transition zone, and qubits 6 and 7, the most weakly coupled, collapse toward noise. At a spectral flatness of 0.813 Gradient is the second noisiest schema. Because it shares Star's exact connectivity and differs only in this decay profile, the contrast between the two isolates the effect of coupling strength on hardware behavior directly: an identical hub topology produces convergence toward a shared shape at uniform strength, and a foreground-background separation at graded strength.

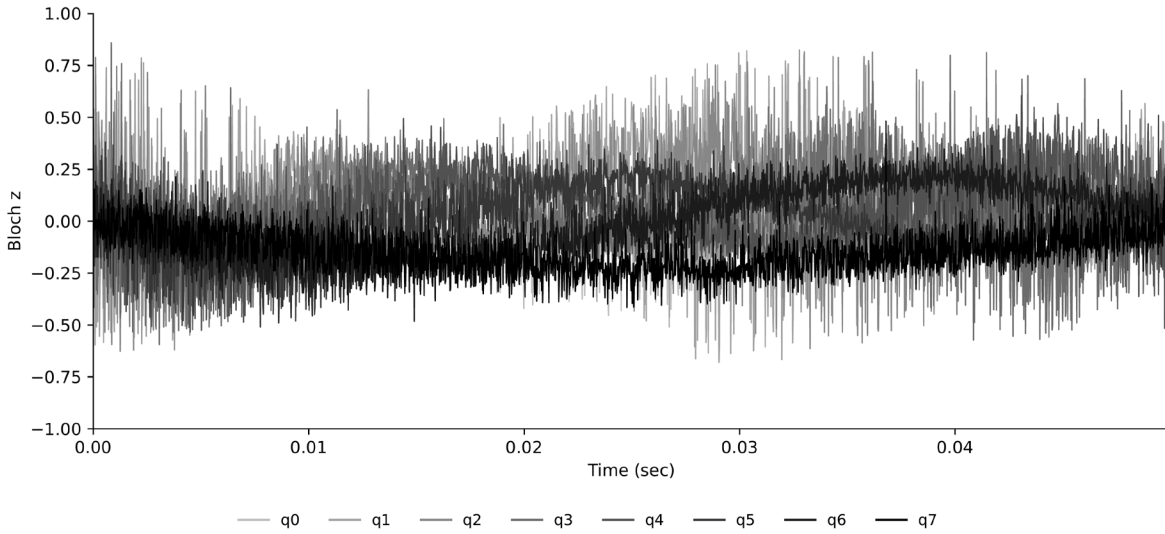


Figure 16. Hardware waveforms for the Gradient schema, hardware amplifying the decay into gestural foreground qubits and a receding, noise-ward background.

Schema 8: Islands

As shown in Figure 17, schema 8 consists of two fully independent four-qubit groups, each closed into a ring: $RZZ(\theta, 0,1)$, $RZZ(\theta, 1,2)$, $RZZ(\theta, 2,3)$ and $RZZ(\theta, 0,3)$ forming the first island, and $RZZ(\theta \cdot 3/2, 4,5)$, $RZZ(\theta \cdot 3/2, 5,6)$, $RZZ(\theta \cdot 3/2, 6,7)$ and $RZZ(\theta \cdot 3/2, 4,7)$ the second, with no connection between the two groups. The second island additionally receives a phase rotation, $Rz(\theta \cdot 0.3)$, on each of its members. The two are therefore structurally parallel but not identical: the second is coupled half again as strongly and carries a phase layer the first does not. The topology is a partition, as in Pairs, but with internally connected groups.

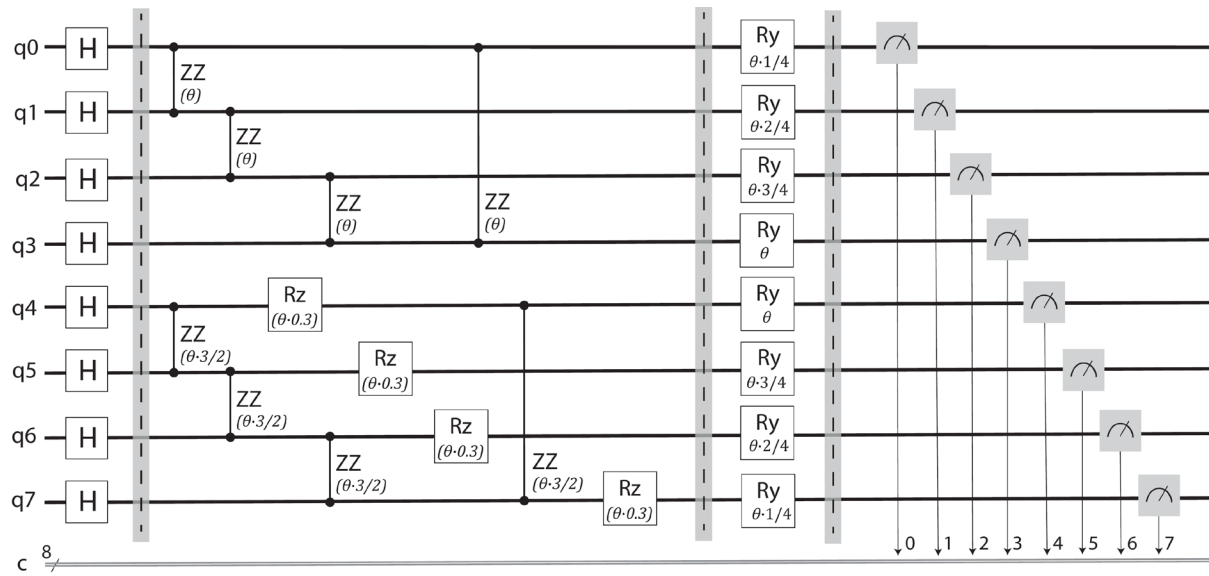


Figure 17. The Islands schema circuit, two independent four-qubit rings, the second coupled half again as strongly and carrying an added phase layer.

Figure 18 shows the second most tonal material of the eight at a spectral flatness of 0.566, with hardware holding amplitude at 1.03 of simulation while retaining 0.20 of its shape. The two islands diverge in character. The first, qubits 0 through 3, is more chaotic and more internally differentiated. The second, qubits 4 through 7, is comparatively coherent, its members tracking one another more closely than those of the first, though the near-identity of qubits 4 and 5 in simulation does not survive execution. Qubit 7, the second island's terminus, shows the clean periodicity seen at the same position in Chain. The two groups are not identical in the executed circuit, the second being coupled half again as strongly and carrying an additional phase layer, so this divergence follows in part from the design rather than from the hardware alone.

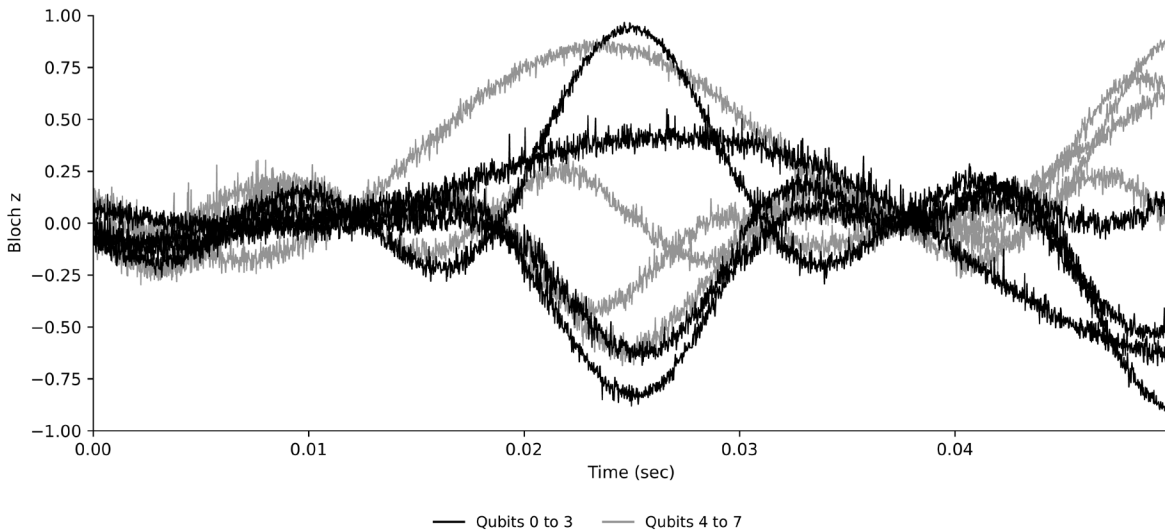


Figure 18. Hardware waveforms for the Islands schema, the two groups diverging in character, with the second island's terminus qubit 7 showing clean periodicity.

Transducing Measurement to Audio

The transformations described in this section change the scale of the measured waveform, not its structure. In the same way an electrical transformer converts a signal from one voltage to another without altering the relationships it carries, the operations detailed below act uniformly on the measured signal to bring it into the range of human hearing, without interpreting, selecting, or re-encoding what the signal represents. The magnitudes of these operations, how far to transpose and how far to stretch, were determined by ear. What follows from the uniformity of the operations is that no such choice alters the relationships the waveform carries: a different transposition would place the material in a different register without changing which qubits correlate, how their amplitudes stand relative to one another, or the shape of any trajectory. This distinguishes these operations from the interpretive mapping function at the center of sonification. The relationships between qubits established by measurement, amplitude, correlation, decoherence, survive every transformation described below intact; only their scale changes.

As a result of the timescale at which quantum circuit execution occurs, the audio material within each raw waveform is extremely compressed. Though the relative quantum values were strictly maintained for authenticity to the underlying measurement, the waveforms required extreme scaling to bring them into the range of human perception and to make them useful as auditory material. Without this transformation, the compositionally relevant content encoded in each waveform would remain hidden. The duration of each raw waveform is determined directly by the number of measurement steps in the circuit (2,400) divided by the target sample rate, one sample per step, producing a 0.05-sec clip at 48 kHz. The amplitude of each sample is the measured Bloch z -expectation value at that step, which is a number between -1 and 1. The frequency content of this raw waveform, by contrast, is not designed; it is an incidental byproduct of how quickly the measured values oscillate across those 2,400 steps, compressed into the extremely short duration. Thus, the unscaled results are an audio impulse as opposed to a musical tone, a natural consequence of the timescale at which the underlying quantum bits evolve.

Conversion from measurement to audio is direct. Each qubit's sequence of measured expectation values is written to a mono 24-bit WAV file at 48 kHz, the value measured at step n becoming the amplitude of sample n . A single scaling factor is then applied uniformly across the file to bring the waveform to full scale, a normalization later reversed during amplitude staging so that the relative amplitudes among a schema's qubits are restored. No interpolation, resampling, filtering, or windowing intervenes, and no value is selected, weighted, or reinterpreted. Every transformation described in the remainder of this section operates on the audio file produced at this step, not on the measurement data.

The first step in the scaling of the quantum waveforms required transformation in the frequency domain. Using a digital audio workstation (DAW), the frequency of each waveform was raised through successive octaves, one at a time, until a viable

listening experience began to emerge. Interestingly, raising the frequencies during the first few octaves made them sound perceivably lower: an oddity for a future spectrographic study.

The effect of this transformation is apparent in the raw and transposed waveform diagrams. Figure 19 diagrams the raw quantum waveforms for each qubit in the Star circuit. Figure 20 diagrams the same waveforms after the transpositions. Where the raw waveforms could be described as indistinct, the transposed waveforms generally reveal eight distinct patterns. This is the timbral quality of each qubit emerging according to the influences of entanglement, interference, and decoherence inherent to their associated circuit topology and execution after the high-frequency noise was raised beyond the range of human audibility.

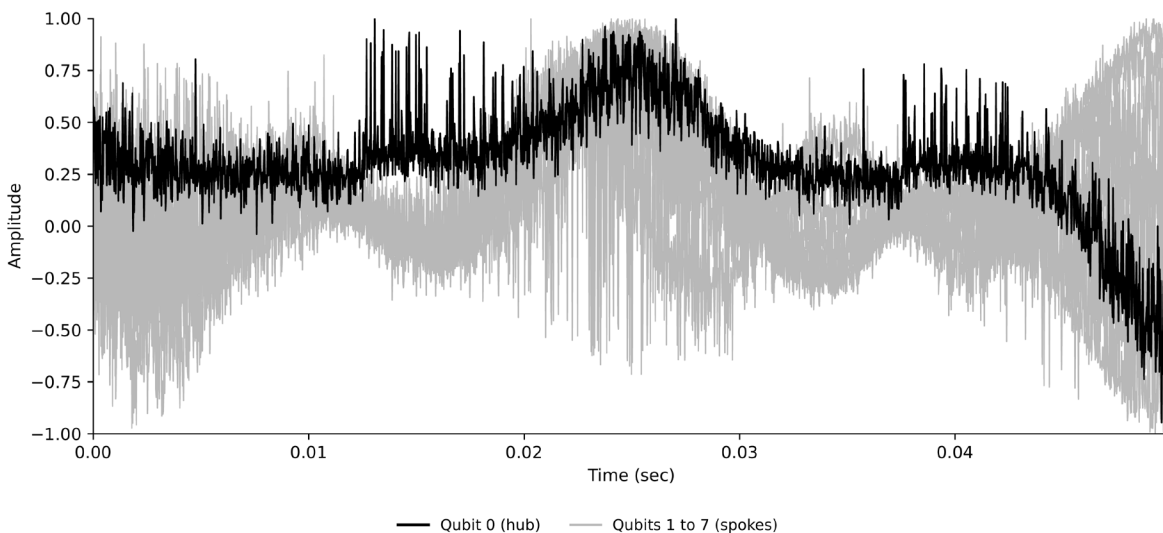


Figure 19. The raw Star waveforms for all eight qubits, an indistinct wash before scaling into the range of hearing.

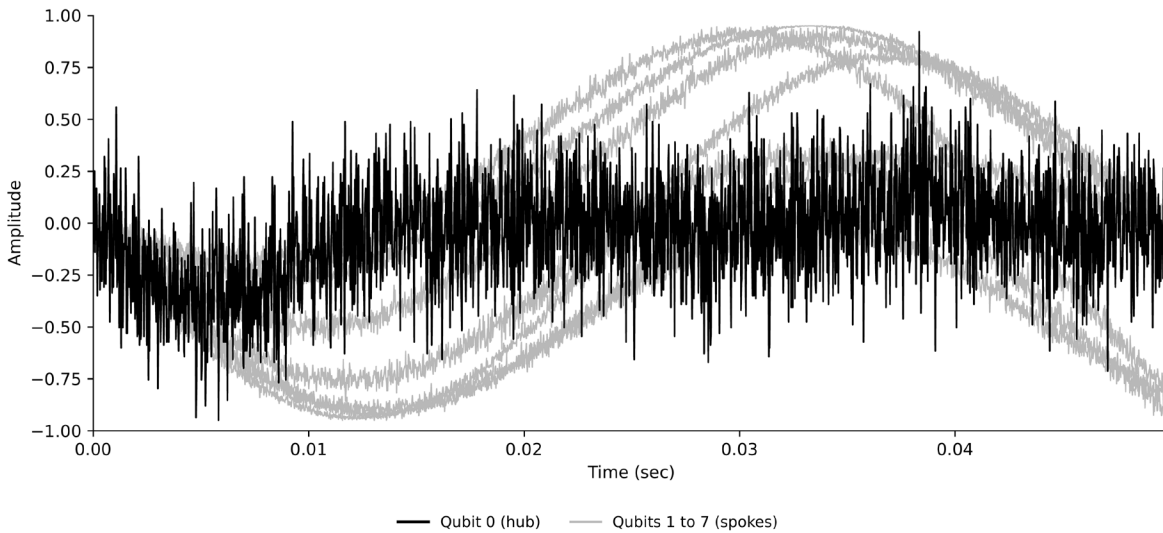


Figure 20. The same Star waveforms after frequency and time-domain scaling, from which eight distinct timbral patterns emerge.

The next important step in the transformation of the 0.05-sec waveforms into a humanly palatable condition had to do with the time domain. Within human temporal perception, the information in each waveform was compressed into an extremely short duration. This is expected considering the timescale at which quantum circuit execution occurs. To adequately scale the waveforms the same DAW was used to time stretch them, extending each to a target of several seconds, long enough for the material to unfold within human temporal perception. This extreme lengthening did not introduce any noticeable digital noise or other forms of signal degradation.

Another important editing step involved DC offset. The raw waveform CSV data were normalized between -1 and +1, which in theory should have balanced each waveform evenly above and below zero. In practice, the DC offset tended to cluster above or below zero for extended periods within a given waveform. Working in the DAW improved this but did not fully resolve it. Because, in this case, an amplitude envelope's transitions do not necessarily align with a zero crossing, applying an

envelope to a waveform with a persistent offset introduced audible discontinuities at those transition points.

Though the resulting waveform's overall amplitude (now measured conventionally, as an unsigned value between 0 and 1) had been normalized, it nonetheless had to be increased in 6-dB increments, repeated as needed, until it arrived within the desired range relative to the other samples. The per-file normalization applied at conversion was in this way reversed by a scaling factor applied to each sample, restoring each qubit's amplitude relative to the fundamental. Since the purity, or decoherence, of the individual qubits determined the amplitude of the ancillary qubits relative to the fundamental qubit(s), this was an important timbral factor. Finally, a brief amplitude fade was applied at the head and tail of each sample to avoid discontinuities at its boundaries.

Ultimately, each entanglement topology produced a distinctive sonic signature. For example, the Star topology generates hierarchical timbres with a dominant fundamental, while the pairs topology creates distinct dialogues between correlated voices. The gradient topology's amplitude roll-off across qubits produces a clear foreground-background timbral separation, with strongly coupled qubits dominant and weakly coupled qubits receding toward the noise floor.

The process of stretching audio waveforms to find the otherwise hidden, micro-acoustic aspects of the audio waveforms is a process that can be described as mining emergent quanta. It revealed the timbral and rhythmic depths, the inner time structures of the quantum-generated waveforms that might have otherwise remained hidden (Miranda 2002; Rhoades 2013; Stockhausen 1959).

Correlation Analysis

Whether entanglement topology survives in the audio domain can be tested directly. For each schema, the Pearson correlation coefficient was computed between

every pair of the eight qubit trajectories across all 2,400 measurement steps, in both the simulated and the hardware condition. Each pair was then classified according to the circuit's entanglement graph: a pair is coupled if a two-qubit entangling gate connects those qubits directly and uncoupled otherwise. Table 1 reports the mean absolute correlation for each class (magnitude is used because a strong anti-correlation still reflects a shared relationship between trajectories) and the separation between them. Because the two conditions share the same parameter sweep and the same topology and differ only in the presence of hardware noise, the simulated columns serve as a control against which the hardware columns can be read.

Table 1. Mean Absolute Correlation between Qubit Trajectories by Entanglement Coupling. Sim. = noise-free simulation; Hw. = Tuna-9 hardware; C = directly coupled pairs; U = uncoupled pairs; D = difference

Schema	Sim. C	Sim. U	Sim. D	Hw. C	Hw. U	Hw. D
Star	0.225	0.790	-0.565	0.307	0.370	-0.063
Chain	0.438	0.429	+0.009	0.593	0.304	+0.288
Ring	0.763	0.713	+0.050	0.673	0.361	+0.313
Pairs	0.929	0.304	+0.625	0.511	0.372	+0.140
Tree	0.460	0.614	-0.154	0.206	0.330	-0.124
GHZ	0.805	0.808	-0.003	0.529	0.201	+0.328
Gradient	0.427	0.363	+0.063	0.195	0.064	+0.131
Islands	0.653	0.280	+0.374	0.447	0.370	+0.078
Mean	0.587	0.538	+0.050	0.433	0.296	+0.136

Consider first the simulated condition, in which the circuits execute without hardware noise. There, the measurements do not support a general relationship between entanglement and waveform correlation. Averaged across the eight

schemas, coupled pairs correlate at 0.587 and uncoupled pairs at 0.538, a separation of 0.050. Entangling two qubits does not on its own produce related waveforms.

Where the relationship does appear it appears decisively, and it appears in the two schemas whose design isolates it. Pairs separates 0.929 against 0.304, and Islands 0.653 against 0.280. In both, entanglement partitions the eight qubits into groups with no connection between them, and that partition is recovered from the waveforms alone, without reference to the circuit. In simulation, then, topology is legible in the audio when the topology is a partition.

Hardware execution reverses this picture and does so consistently in both directions. In every connected topology the separation widens: Chain from 0.009 to 0.288, Ring from 0.050 to 0.313, GHZ from -0.003 to 0.328, and Gradient from 0.063 to 0.131. In both partitioned topologies it collapses, Pairs from 0.625 to 0.140 and Islands from 0.374 to 0.078.

One mechanism would account for both directions. Two-qubit entangling gates are the dominant error source on current hardware, and their errors act on both members of a pair together, so noise introduced during execution would be expected to follow the entanglement graph. Where the graph is connected, that propagation traces the graph and renders it measurable where noise-free simulation does not. Where the graph is partitioned, the same propagation crosses the designed boundaries and erodes them. These measurements do not isolate that mechanism. The circuit executed on hardware is not the circuit as designed: the compiler maps coupled qubits onto physically adjacent processor qubits, and topologies that exceed the processor's connectivity require additional swap operations that deepen the circuit unevenly across schemas. Correlated two-qubit gate error, crosstalk between neighboring qubits, and differences in compiled depth are therefore confounded here, and any of them would produce the observed signature. Separating them

would require executing the same logical topologies under deliberately varied physical mappings, which is a direct and inexpensive next experiment.

As is illustrated in Figures 21 and 22, what the measurements do establish is that hardware execution restructures the correlation relationships in a topology-dependent way, and that the independence built into Pairs and Islands is a property of the circuit rather than of its execution. The divergence between the two conditions is visible directly in Figure 23, which sets the simulated and hardware trajectories of Chain qubit 7 side by side.

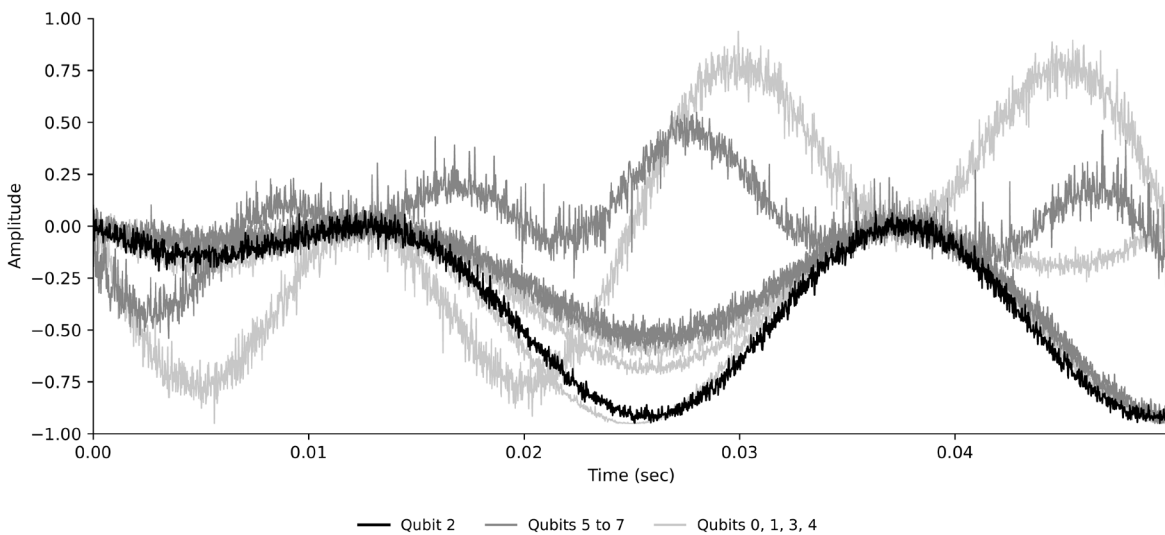


Figure 21. The processed Ring waveforms, illustrating how hardware execution restructures the correlations among qubit voices.

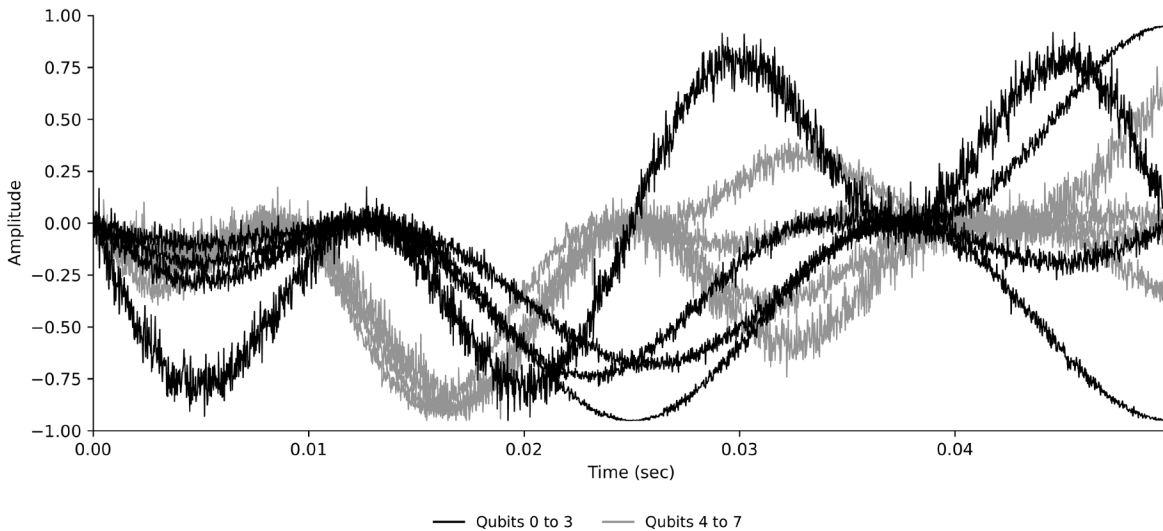


Figure 22. The processed Islands waveforms, the two designed groups reading as distinct timbral families.

Star and Tree separate negatively in both conditions, and the reason is instructive rather than anomalous. Star's hub qubit has a simulated standard deviation of 0.036, against a shot noise floor of approximately 0.031 for 1,024 shots. It is flat, as Figure 24 shows. Entanglement with seven partners leaves the hub maximally mixed, its Bloch vector collapsed toward the origin, and a qubit with no trajectory cannot correlate with anything. Tree behaves the same way near its root. The relationship between entanglement and correlation is therefore not monotonic. Coupling creates shared structure between qubits, and heavy coupling destroys the individual structure available to be shared. This is the quantitative account of a pattern visible throughout the schema results, that moderate and asymmetric entanglement yields differentiated material while maximal entanglement yields none.

These measurements bear on relationships between voices rather than on timbre. In the author's compositional practice, waveforms drawn from a coupled pair are heard as belonging together, and the partitioned schemas were chosen for the composition on that basis. That judgment is a listening observation rather than a

measured result. What the hardware columns establish is that the grouping is weaker in the executed material than the circuit design predicts, which is a real constraint on how far entanglement topology can be relied upon as a contrapuntal device.

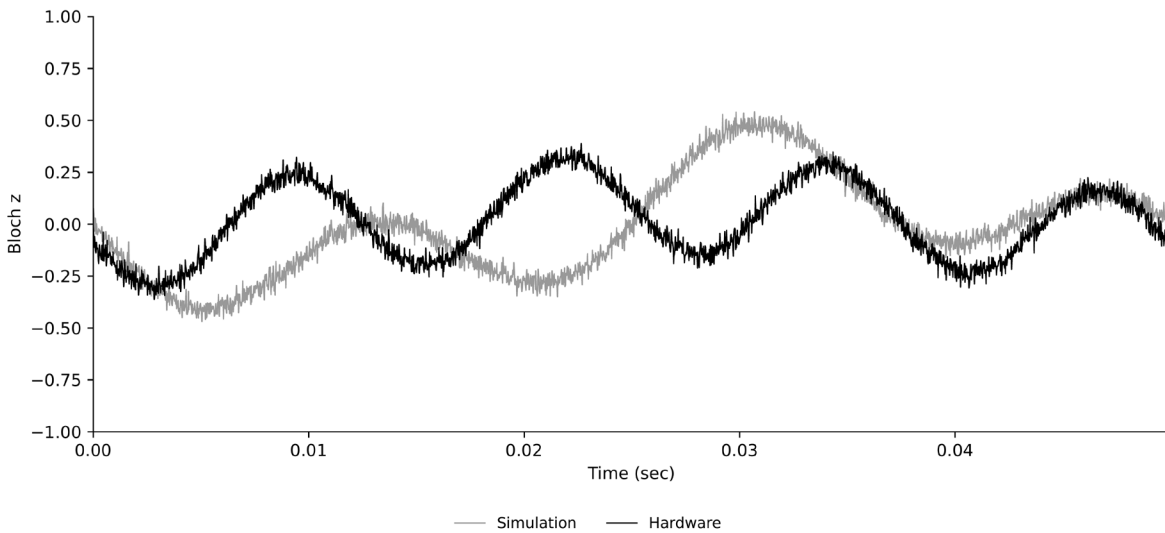


Figure 23. Simulated (gray) and hardware (black) trajectories for Chain qubit 7, whose shared periodicity settles at a different rate in each condition.

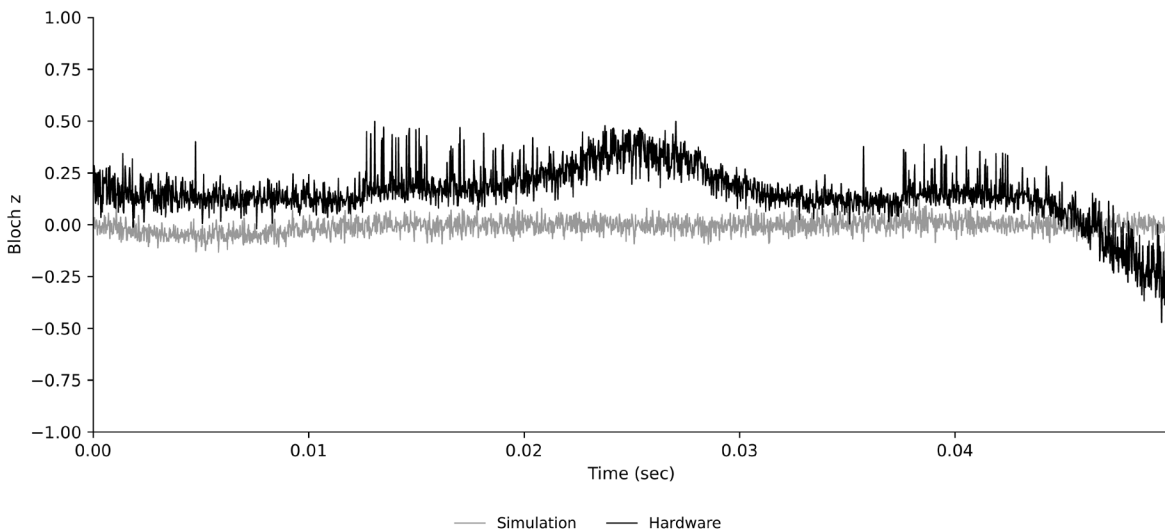


Figure 24. Simulated (gray) and hardware (black) trajectories for Star qubit 0, the hub nearly flat in simulation yet sweeping its full range under hardware.

Compositional Results: *The Infinite and the Infinitesimal*

Ultimately, these quantum computationally derived waveforms were used as base samples to create the composition, *The Infinite and the Infinitesimal*. Using Csound, Cmask, and Score-Based Sampling processes (Rhoades 2020), this 32-channel composition is 18 minutes and 23 seconds in length. It demonstrates a broad range of timbres and rhythms concealed within the microstructures of the quantum-computer-generated waveforms.

The audio waveforms were used in the composition in two ways. First, the eight samples per schema were combined in the originally intended manner. The fundamental waveform was mixed with the seven ancillary waveforms, maintaining the amplitude relationships determined by the entanglement strengths. This created eight base samples, one per schema, each consisting of complex harmonic structures. Second, each waveform was used independently, providing 64 total base samples. Though the harmonic structures of these samples were not as complex as those of the first approach, when combined throughout the composition they provided a way to intermix samples between schemas, creating another sonic palette with which to compose.

Score-Based Sampling employs a stochastic approach that determines the frequencies, amplitudes, start times and durations (creating varying densities), spatializations, and many other characteristics of each event of the Csound score. Describing this process is beyond the scope of this paper but detailed information can be found in various references (Rhoades 2005, Rhoades 2020).

The composition's title, *The Infinite and the Infinitesimal*, is a compressed statement of the paper's central mechanism, immense density at one time scale compressed into a grain, then expanded outward through domain transformations into an extended composition. It exposes the compositional potential of transducing the quantum wavefunctions and entanglements directly to a musical experience. *The*

Infinite and the Infinitesimal can be heard here:

<https://quantumcomputationalcreativity.com/creative-works#RFHS>

Conclusions

This paper presented a methodology for generating audio waveforms directly from quantum circuit execution, with no intermediate symbolic or data-mapping layer standing between quantum measurement and sound. Each of the eight schemas discussed in the Circuit Topology section was first executed in noise-free simulation for validation, then executed on Quantum Inspire's Tuna-9 hardware. This sequencing provided the systematic hardware-versus-simulation comparisons reported in the Correlation Analysis section that isolated what hardware noise specifically contributes.

Two findings anchor this method's central claim. First, as shown in the Correlation Analysis section, entanglement topology is recoverable from the waveforms themselves, most clearly where that topology partitions the qubits into isolated groups, and hardware execution alters this recoverability systematically, widening the separation between coupled and uncoupled pairs in connected topologies and collapsing it in partitioned ones. Second, this same topology governs how a circuit's waveform transforms under real hardware noise, and this transformation is not uniform across schemas. Star topology's fundamental qubit, nearly flat in simulation, swept through its full amplitude range under hardware execution. Ring and Chain preserved their simulated shape while gaining textural complexity. GHZ's maximal entanglement collapsed to near-identical noise in both conditions. Schemas with moderate, asymmetric entanglement (Star, Gradient, Tree) proved compositionally fertile, while maximal-entanglement schemas were less so.

Because the waveform is the measurement, hardware noise perturbs the acoustic signal directly, with no intervening representation to absorb or filter it, which

demonstrates that hardware noise carries different consequences for this methodology than for parameter-mapping approaches. This addresses the question posed at the outset: can quantum waveforms be music and can the design of a quantum circuit itself become an act of composition. The sample derivations and the compositional results discussed regarding *The Infinite and the Infinitesimal*, demonstrate that both answers are affirmative. The circuit's topology is heard, its entanglement structure is heard, and the hardware's own imperfection is heard as a distinct and compositionally valuable voice rather than an error to be corrected.

This study also exposes clear limits that define the immediate direction for future work. The eight schemas presented here are, by design, simple, illustrative points in a much larger design space. More elaborate circuit architectures, deeper entangling layers, dynamic or mid-circuit measurements, structures that combine multiple topological principles within a single circuit, are ripe for exploration and are a natural next step now that this method's basic viability has been established.

A further limitation is the narrowness of the timbral range produced. The same analysis reported in Table 1 shows that waveforms drawn from different schemas prove nearly as correlated with one another as waveforms drawn from the same schema, at mean absolute correlations of 0.296 and 0.330 respectively, and the spectral flatness of all eight schemas falls between 0.535 and 0.826, occupying only the upper, noise-like portion of the available range. Entanglement topology, then, governs the relationships among voices within a circuit far more strongly than it governs the character of the material overall. This follows directly from the design of the study. All eight schemas share the same four-stage design, superposition, entanglement, differentiating rotation and measurement, and an identical parameter

sweep, differing chiefly in their entangling pattern. That common design served its purpose. Establishing a wider palette is a separate undertaking, one that will require varying the layers held constant here, and it is a direct next step now that the effect of topology alone has been isolated.

Scale itself poses a further, more fundamental constraint. The classical simulation, used throughout this study as a noise-free reference against which hardware results were measured, will undoubtedly become computationally intractable well before circuit sizes reach even a few dozen qubits. As this methodology is extended to the larger qubit counts increasingly available on current hardware, the simulation-based comparisons central to this paper's findings will no longer be viable, and hardware execution will need to be tested, validated, and evaluated on its own terms. A related caveat applies to the hardware findings themselves. Each schema was executed once, so the consistency of a given machine's signature across separate executions remains untested, and establishing it would require repeating a schema and comparing the two runs directly.

Finally, the transduction methodologies presented here have thus far been developed for audio alone. It is posited here that the same quantum measurements that yield an audio waveform can equally establish visual parameters. Thus, an extension of this methodology to the production of visual music composition is a natural and immediate direction for future work, one that would test whether the perceptual and structural findings reported here for sound extend to the visual domain as well.

Acknowledgments

The author would like to thank Quantum Inspire for access to circuit testing and execution on their Tuna 9 backend and to the IDIA Lab at Ball State University for their support of time allocation for this project.

The author collaborated with Claude (Anthropic) throughout this research for circuit design and code development, for analysis of measurement data, and in drafting and revising this manuscript. All circuit designs, compositional decisions, analytical conclusions, and final text were determined and verified by the author, who is solely responsible for the content.

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