Quantum Harmonies: An Artistic Exploration of Geiger Counter Measurements and Simulated Quantum Circuitry for ISQCMC 2023

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Abstract. *"Quantum harmonies" is an art project that intertwines geiger counter measurements with a simulated quantum computing circuit, translating emerging dynamics into a captivating musical experience.*
Following an approach, where the most meaningful relationships between the concepts are tried to be established, the project explores the notions of superposition, entanglement, measurement, and effects of radiation.
Drawing inspiration from the many-worlds interpretation of quantum mechanics, the life of a hypothetical musical quantum organism whose sole sensory organ is a geiger counter was modeled. Characteristic effects taking place during it's journey are portrayed visually and audibly, aiming to offer an immersive way of understanding the dynamic relationship between geiger counter measurements and quantum concepts.

1 Introduction

Although the promised advantages of quantum computing are yet to be fully realized due to the current limitations in maintaining physical quantum circuits of arbitrary complexity, the advent of simulated quantum circuitry and the accessibility of cloud-based hardware are opening unprecedented opportunities for interaction and experimentation, as can be seen by the amount of resources and services offered online like IBM Quantum ([1]).

Even with the limitations of current quantum hardware, a considerable range of meaningful algorithms exist. In parallel with the exploration of quantum technology to solve mathematical problems, a huge part of the exploration takes place in field of generating music ([2]), similar to how conventional computers in their advent were explored for their musical capabilities ([3]).

A range of ways to generate music through computers exists in the realm of algorithmic composition, while, naturally, vast materials on musical compositional styles and techniques can be obtained. Depending on the input of a compositional algorithm, the task of the programmer must be to find a way for the moving parts to create a meaningful expression in music, as opposed to taking over what the computer outputs as-is.

On that notion, this paper explores the relationship of aspects of quantum mechanics in regards to algorithmic composition, if the input to the system were geiger counter measurements.

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As will be shown in this paper, this perspective offers for quite meaningful relationships between the information that the measurements carry and quantum circuit properties (like superposition, entanglement, measurement), for which in turn, with the help of a novel quantum instrument, Q1Synth [4], equally meaningful translations to expressions in music were found.

With respect to how musical perception takes place in humans, based on the Implication-Realization model of melodic expectation [5], the journey of a virtual quantum organism was modeled, as it experiences different events in life, that lead to it taking different pathways. A meaningful connection to the many-worlds interpretation of quantum mechanics is established and translated into a musical journey.

Following this section, the theory behind the different concepts in place is introduced in section 2. With the knowlege about the concepts, the approach to find meaningful relationships between them is outlayed in section 3. The implementation of the overall system is described in section 4, together with explanations on the musical implications. The paper finishes with a conclusive statement in section 5, also highlighting limitations that serve as an outlook towards possible expansions of the model.

2 Concepts

In this section, concepts used in the project, as random number generation (RNG), geiger counter measurements, and a specific set of basic concepts regarding musical perception, style and technique - those that were evaluated to be most feasible for the use in the project - are quickly introduced.

In order to omit a introduction to quantum computing from scratch, concepts like qubit, superposition, entanglement, measurement, quantum gates are not being introduced independently. Instead, as they take their place within the other concepts, they are explained with the intention of giving a newcomer to the topic an example to relate to. The reader is encouraged to refer the concise introduction to the basics gate-based quantum computing in the appendix of [2].

2.1 Pseudo RNG and true RNG through quantum computing

Although being such a simple quantum circuit (depicted in figure 1), the ability for true random number generation is a significant achievement. Conversely, the numbers of

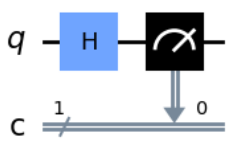

Figure 1: A quantum circuit RNG. Generated using Qiskit (see [6])

deterministic RNGs, can not be called truly random and are therefore calles pseudorandom. Although having their application and being more readily available, they do not solve some of the problems, for which a non-deterministic true random number is necessary. To just highlight one of the most crucial aspect of the difference in between them: if one gets knowledge of a deterministic RNG algorithm, one gets knowledge of the complete and only possible sequence of numbers that the deterministic algorithm can produce. This has large implications in e.g. information security, where an attacker that would get knowledge of a RNG seed for a cryptographic operation, could potentially reverse the operation to the point where a password is obtained.

In quantum computing, there is an inherent principle that allows for the generation of true non-deterministic random numbers, that can not possibly be predicted. Namely, the Heisenberg uncertainty principle states, that certain pairs of physical properties of a particle cannot be measured simultaneously. A very common example for that principle is Schrödinger's Cat, but in the realm of quantum mechanics, this principle applies to a qubits' state vector in the state called *superposition*. A qubit is in superposition at every point in time where it is not measured. As a result of transforming the qubit into an equal superposition through a *Hadamard* gate (the block in 1 with an H), and then measuring it (the block in 1 with an analogue scale symbol), the qubit collapses to one of it's *basic states* (commonly represented using Dirac notation: $|0\rangle$ and $|1\rangle$), yielding in true random fashion either a 0 or a 1 in terms of classical bits.

For a complete newcomer to the topic, is worth mentioning, that meaningful quantum algorithms, that do more than RNG, manipulate and transform the states of multiple qubits using a range of quantum gates, to exploit their probabilistic nature. Among them, some allow for *Entanglement*, which is in simple terms a conditional dependency between multiple qubits.

2.2 True RNG through geiger counter measurements

Another popular and reasonably achievable way of generating random numbers is through the measurement of environmental background radioactivity. For that, a high voltage is applied to a tube containing a specific gas, a *Geiger-Müller tube* (see 5). When ionizing radiation enters the tube, it ionizes the gas inside, creating positively charged ions and free electrons, which through the voltage are accelerated towards the electrodes, resulting in an electrical *pulse*. Because one can not (without an extensive laboratory detection system capable of identifying the particle's time of arrival upstream) estimate the time at which the pulse occurs, this is under all normal circumstances considered a true random event in time, which can be translated into a number by measuring the moment of occurence.

2.3 Measuring radioactivity with a Geiger-Müller tube

Arguably, *sievert* (Sv) is the most relevant unit of measurement in a Geiger counter. This unit represents the stochastic probability of health risks caused by radiation-induced cancer and genetic damage, and quantifies the overall dose of radiation to which an organism was exposed over time. In this regard, another instrument commonly used to measure the overall dose of radiation exposure is a dosimeter. These devices can be relatively simple and are often carried by individuals working in radioactive environments. Some dosimeters are designed without electronics; instead, they utilize photographic materials that darken when exposed to ionizing radiation. By comparing the darkness of the material before and after being in a specific situation, the dosimeter provides valuable information about the accumulated dose in sieverts.

While a dosimeter can only provide information on the overall sievert accumulated, a geiger counter allows for real-time detection of radiactive sources. For this purpose, the seperate pulses are aggregated over a specific time interval, usually measured as *counts per second* (*CPS*) and *counts per minute* (*CPM*), to provide a current intensity value. The typical unit displayed on a Geiger counter is *microsieverts per hour* ($\frac{\mu\text{Sv}}{\text{h}}$). Consequently, this also means that only after a significant amount of time, the value can be regarded as confident.

The calculation of the sievert value also depends on the sensitivity and corresponding conversion factor (*CV*) of the specific Geiger-Müller tube used. The formula states as follows:

$$\frac{\mu\text{Sv}}{\text{h}} = \text{CPM} * \text{CV}$$

For the specific tube used in this project, the soviet *SBM-20* Geiger-Müller tube, the calculation of the proper CV has been elaborated upon (see [7]) and concluded to be 0.00812.

It is worth mentioning that an output pulse always has the same magnitude, regardless of the actual energy a particle has carried. This limits us to not be able to differentiate between different types of radiation. Regarding that, the SBM-20 is only sensitive to beta and gamma, but not alpha radiation.

2.4 Half-Life in radioactive decay

All radioactive materials have unstable nuclei and undergo a natural process called decay. According to quantum theory, it's impossible to predict exactly when a particular atom will decay, no matter how old it is. However, for a large group of identical atoms, we can measure the time it takes for half of them to decay. This time is called *half-life*.

This means that after the "first" half-life of a specific radioactive mass, it will take an equal amount of time for the mass to reduce to half again. This characteristic gives rise to the term *exponential decay*. The formula for the amount of remaining radioactive mass after a certain amount of time is as follows, with t_{half} as half-life, M the current amount of mass, and M_0 the initial amount of mass:

$$M(t) = \frac{M_0}{2}^{\frac{t}{t_{\text{half}}}}$$

The specific half-life values for different radioactive materials are well-known. For example the half-life of the beta-radiating tritium, a material popularly used for perpetually-glowing illumated wristwatches (banned for use in some countries), is $t_{\text{half,tritium}} = 12.32$ years.

2.5 The Implication-Realization model of melodic expectation

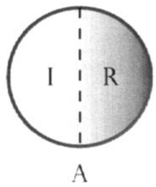

Figure 2: An implication I and realization R combined in a schema A. Source: [8] (p. 374)

First introduced by Eugene Narmour in [9], and elaborated upon in other works (most relevantly in [5]), the application of schema theory to music presents a fascinating concept of which a few core mechanics are used in the context of this project:

- During the experience of listening to a musical piece, an *implication* (denoted as I) represents a distinct segment of the music that evokes a particular association or meaning in the listener at the present moment.
- Subsequently, the specific realization of that implication, denoted as *R*, refers to the subsequent part of the musical piece — the changing musical scenery that the listener encounters after the implication part.
- The combination of implication I and realization R forms what is called a *schema*. In psychological terms, a schema represents the concept of how humans perceive information through their senses and attribute meaning to it. In the context of music, a schema A can be seen as an "expectation" that the realization R, such as an upcoming musical event, will follow if the implication I, or prior musical information, occurs.

Figure 2 depicts a graphical representation of a schema.

An Implication can also have multiple realizations (see figure 3). To give an example for a popular implication and realization in the realm of classical music: the build-up of tension (I), that is either followed by more tension (R1) or a resolution in the music (R2).

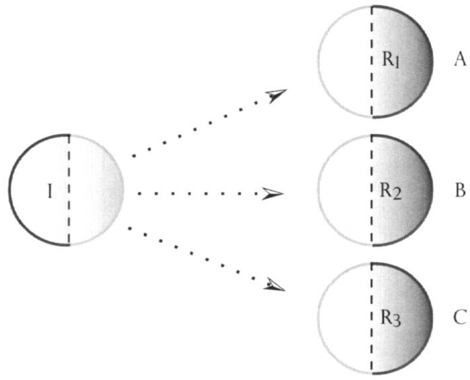

Figure 3: An implication I can be followed by multiple realizations R_1, R_2, R_3 which in combination are considered seperate schemata A, B, C. Source: [8] (p. 374)

2.6 A composers' skill: Il Filo

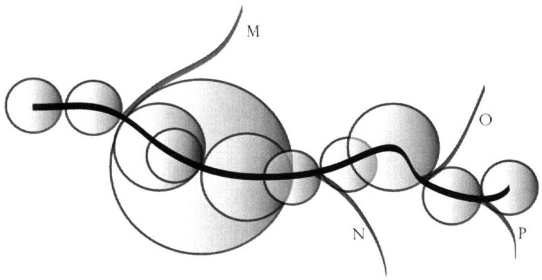

Figure 4: Different pathways M, N, O, P, that a composer might take. Source: [8] (p. 378)

Referring to a quote from Mozart's in a letter dated August 13, 1778, he describes features of a good maestro: "good technical composition and the arrangement of material: il filo". Here, the term *il filo* (the thread), as elaborated upon in [8], accurately signifies the decisions a composer might make to shape the *path* of a composition (see figure 4). A composer could choose to adhere strictly to existing pre-defined compositional rules when composing a sonata, resulting in a piece with a unadventurous and uninspired path. Conversely, a skilled composer may skillfully spin the thread, creating a path that explores lesser-known musical avenues to be able to offer profound new insights.

3 Approach

In this section the approaches behind the final choices taken, in search of a most meaningful realtion between the introduced concepts, are alaborated upon. These choices define the model of our imaginary musical quantum organism for later implementation.

3.1 Superposition of a qubit and geiger counter pulses

While the position of the state vector of a qubit in superposition cannot be known in between measurements, according to quantum mechanical principles, the question is how logical or meaningful it would be to make any assumptions about the behavior in superposition other than that.

What we do know however is, that the position of the state vector *is* in a distinct position at the exact point of measurement, from which it collapses to one of the poles.

One approach for using the input pulses could have been to initiate truly random measurements, but this was considered infeasible and subsequently rejected, because it counterfeits the generation of meaningful information as it does not matter if we take the measurement (for our quantum RNG circuit) delayed or not. A measurement at a random point in time would have the same meaning, as a measurement at any point in time.

Therefore another meaning needs to be given to the *time of arrival of a pulse*. With the unsolved question how a qubit "behaves" in superposition still in mind, became evident that one assumption about its state could be made as an artistic choice. Although not scientifically accurate, this assumption could be made without completely disregarding the qubit's nature: it's position could be considered truly random. By adopting this consideration, it becomes apparent that the truly random nature of Geiger counter pulses could represent the positions occupied by a qubit's state vector at the time of pulse arrival

The following decision was made based on this understanding:

- ▶ The true random occurence of pulses relates to the true random position of a qubits' state vector in superposition at the moment of pulse arrival.

It could also be argued that this resembles a kind of measurement that does not lead to a collapse, but takes a snapshot of the position of the state vector as it is "moving" in an unknown fashion.

3.2 Relating geiger counter measurement methodology with the I-R model of melodic expectation

As introduced, a geiger counter needs to accumulate an amount of pulses over a certain period of time to be able to tell with certainty the average value of intensity. Similarly, we can envision an imaginary organism that aims to make sense of a musical piece. This fictional entity perceives the musical pulses as life experiences or implications. By accumulating experiences over time, the organism forms a stable opinion or understanding (schema) of the information received. The realization of the implications is represented by the $\frac{\mu\mathrm{Sv}}{\mathrm{h}}$-value.

Because this offers a meaningful way to relate the stabilizing values of a geiger counter measurement over time, and the stabilizing opinion of a (human) organism forms based on perceived information, the following decision was made:

- ▶ Each pulse represents a distinct information in the life of a the organism, as well as a new position of the state vecto in superposition.
- ▶ As pulses accumulate over time, the organism forms a stable opinion about impression formed through gathered experiences during the current *episode*.
- ▶ When a certain threshold of certainty about the similarity of impressions within an episode is reached, a realization as in the I-R model occurs, completing a schema
- ▶ The point in time at which the $\frac{\mu\mathrm{Sv}}{\mathrm{h}}$-value no longer changes significantly, the condition for the end of the episode is reached, symbolized by the measurement of the qubit

E.g., if the organism would be exposed to normal background radiation, pulses arrive at different timestamps. With the duration of time in between the timestamps, the organism would accumulate the durations of each pulse. Based on the group it is forming and the similarity between the pulses, at a certain point the organism would be able to predict with certain confidence, how many pulses are going to arrive for the current episode. In other words, the organism is fed with environmental informations, it forms an opinions about the nature of the environment and as soon as it has formed a stable opinion, it considers the episode as over, measurement takes place, and information that follow is expected to belong to a new episode.

3.3 Relating compositional pathways with qubit entanglement

The same way as a human composer has its own reasons to consider to take one over another pathway based on experiences made in life, our organism might want to decide if it wants to make one over another decision.

A meaningful mechanism for that can be qubit entanglement, where based on the outcome of one qubit, another qubit is influenced. In quantum computing, for that, there exists the conditional not (CNOT) gate. It entangles two qubits, a control qubit and a target qubit in such a way, that a NOT-operation (bit-flip) is performed on the target qubit only if the control qubit is in the state $|1\rangle$,

To provide the organism with a straightforward mechanism for making compositional decisions, the following choice was made:

- ▶ The collapsed state of the previous qubit influences the measurement of the next qubit in the manner of a CNOT gate, drawing parallels to the decisions a composer might make regarding the a pathway of a composition

3.4 Relating harmonics to the definition of the available paths

Similarly to how a classical composer might implement different realizations in a musical piece, deciding out of a limited range of *suiting* paths, we do not want to leave the control over the possible paths open to whatever the computer outputs without meaning. Different ideas come to mind when thinking how sounds generated by multiple qubits together could meaningfully intercorrelate, but to not overwhelm the profound basic expression that a simple mechansim bears, the following decision was made:

- The available basic states that a qubit can collapse towards, are represented by notes on a musical scale.
- The sounds that qubits can make together are *harmonies*. To form a hamonic chord with the note of a previous qubit, a choice is made among possible harmonics.

The possible paths that are open for the organism to take at a point in time, can also be interpreted in terms of the many-worlds interpretation, in which the universe is regarded as a tree that branches over time, with the branches representing possible realisations of quantum outcomes.

3.5 Relating to half-life

Because taking measurements of radiation not only gives the organism information about the radiation values, but also exposes it, a proper way to reflect that the organism accumulated a specific amount of radiation during an episode would be to make the sound for that episode fade away for a specific duration that reflects the amount.

Therefore the following decision was made:

- The pulses accumulated during an episode could be regarded not as a mass, but as as a specific *material*. The echo of a measured sound should mirror the behavior of exponentional decay of a specific material.
- The half-time of the decay can be based on the amount of pulses aggregated.

3.6 Sonification of the quantum circuit using Q1Synth

Q1Synth is a novel musical instrument, introduced to the public at the beginning of the year (see [4]). It offers an audible representation of the position of a qubits' state vector, the ability to take measurements, as well as several options for modifying the characteristics of the sound such as an upper and lower frequency limit based on a musical scale.

It allows for a straightforwards application of the model as introduced to this point:

- A single qubit can be represented by a single instance of Q1Synth
- The instrument will produce a sound, based on the position of a qubit in superposition
- The parameters of upper and lower frequency limit can be used to implement harmonics
- Entanglement between multiple instances of Q1Synth needs to established externally, as it is not offered as an option directly

An in-depth explanation of Q1Synth is omitted here, and left for later screenshot to serve as an example for a better base of understanding.

4 Implementation

With the exact implementation being made available as source code via [10], in this section the implementation is described as plain language.

4.1 Hardware

The hardware used in this project consist of:

- an ESP32
- connected a self-soldered MightyOhm geiger counter kit including an SBM-20 Geiger-Müller tube (refer to [11]), shown together in figure 5
- a wireless network
- a capable modern desktop computer running Windows 11

4.1.1 Connecting the ESP32 with the geiger counter

I aimed to ensure precise measurement of the exact timestamps of arriving pulses without losing any data or introducing delays caused by other applications occupying the processing unit. To achieve this, I utilited a readily available ESP32 and its pulse counter module (refer to [12]). That way, any time a pulse is registered at the pin routed to the module, an interrupt is triggered, and a measurement can be synchronously taken (as opposed to needing to poll the data at fixed time intervals).

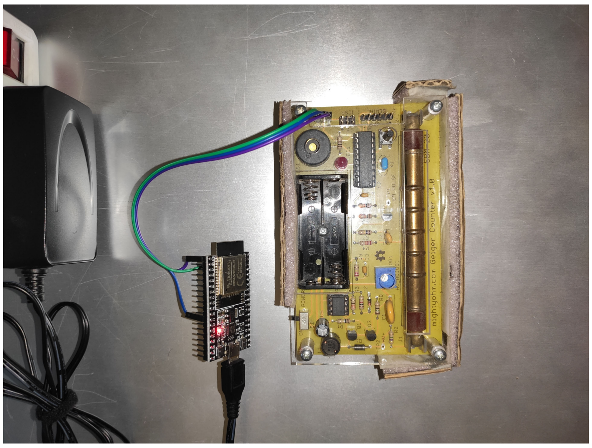

Figure 5: The hardware setup

An additional benefit of using this combination is that the geiger counter can be completely powered by the ESP32's power outlet, as it requires only 3.3 volts.

4.2 Software

While the system was developed and tested using a desktop computer running Windows 11, it is worth mentioning that the system was developed using cross-platform capable components.

4.2.1 Communication between the ESP32 and the desktop computer

As the ESP is interrupted by a pulse, the timestamp in nanoseconds is added to a list. At intervalls of 1 millisecond, it is checked if the list contains any value. If the list contains one or more more values, accounting for the fact that multiple pulses could occur at high radiation levels within 1 millisecond, it is sent to the wireless network that the ESP32 is connected to, using the (real-time capable) MQTT-protocol ([13]).

4.2.2 Q1Synth

As introduced, Q1Synth is a musical instrument and offered as a web-browser-based musical instrument (see([14]), that can be fully controlled via the MIDI protocol.

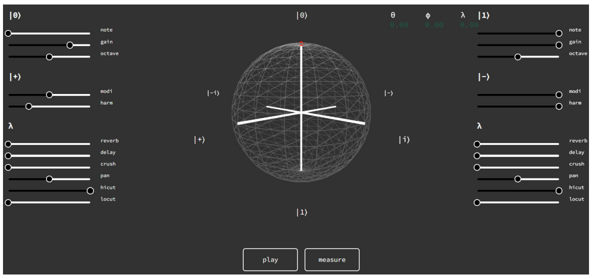

Figure 6: The user interface of Q1Synth

Figure 6 shows the user interface of Q1Synth. At this point it is important to understand that the exact north and exact south pole of the displayed *Bloch sphere* (a visual representation of the states of a qubit using a three-dimensional sphere) represent the basic states that a qubit can collapse to. In Q1Synth, they each correspond to a specific upper and lower note (frequency).

In regard to the importance within the scope of this project, a simplified explanation of the produced sound is given:

- The axis that define the positions of the state vector on the Bloch sphere are θ, ϕ, λ.
- Each axis has a two opposite poles (so-to-say a *north* and *south* pole).
- The inclination that a state vector has, influences different parameters for each axis.

The paramaters considered relevant for the implementation are:

- The inclination on the θ directly correlates to the position in between the poles $|0\rangle$ and $|1\rangle$, which each define a maximum and minimum value for note, octave, and gain. For example if the upper frequency limit was set to 440Hz and the lower frequency limit to 880Hz, the frequency of the produced sound would "swing" in between the range of a full octave, a lower and an upper C, depending on the inclination on θ.
- For ϕ and λ, other parameters of the sound of the sound are influenced, like the amplitude of a seperately configurable modulation envelope for the ϕ-inclination. Most of them are unused in this project
- Another parameter we however do control is the general "reverb" and "delay" of a qubit's completed episode to represent half-life. To control the general parameter, we set the upper and lower boundary to the same value.
- In this project, all other parameters are set to general but in this case completely fixed, sensible value of artistic choice, which in this first implementation was to create a mostly "pure" sound, for which the effect of the deliberately influenced parameters can be distinctly made out without noise from parameters for which no meaningful relationship to the concepts was found so far.

For a handy visualisation of multiple Qubits, multiple Q1Synth instances were organized utilizing the tiling feature of the Vivaldi browser ([15]). See figure 7.

Figure 7: 4 seperate Q1Synth instances

The MIDI input device for each Q1Synth can be set individually, so that all four can be individually controlled

As an artistic choice and for the sake of simplicity also in regard to creating harmonic chords of limited complexity, **4** Qubits will be represented to follow the rules of the model.

4.2.3 Controlling the qubits and implementing the model

The model is implemented in python, using the python-rtmidi library ([16]), and the pytuning library for ensuring harmonics ([17]).

Each Q1Synth now needs to represent a qubit, "experiencing" an episode, therefore 4 virtual midi loopback devices were created using the windows-only tool loopMIDI ([18]). Equivalent alternatives exist for Mac and Linux.

Pulses are collected, resulting in a measurement as soon as confidence about the probability of pulses occuring within that episode. For that, the µSv-value is estimated each time a pulse arrives, and collected in a list within the episode.A different μSv-value results for each pulse, which itself converges to a certain value over time. By calculating the difference in between all μSv-values within an episode and building the average, this *average confidence* (AC) value decreases over time, the more pulses are aggregated. As the value goes below a certain threshold, the *confidence level* (CL), the "organism" deems the episode complete, as through its aggregated experience, it deems itself condifent enough to predict to a certain degree the properties of future pulses for the episode, if it would continue. This results in a varying time period for each episode, for the organism to "feel" confident and the value to converge. It is possible that very similar pulses occur at the beginning of an episode, be already being deemed complete. If exposed to an environment where the radiation levels suddenly increase, it is also possible an episode to take a longer amount of time until the amount of pulses is so large that the AC converges below the CL.

Anytime the AC goes beyond the CL, the qubit is measured and it is proceded with the next qubit (when qubit 4 is measured, it is continued with qubit 1). As a preventive mechanism, the CL starts at 0.05 resembling the common significance level in statistics, but is increased by 0.01 after each 10 pulses.

For determining the frequencies of a qubit, a property of the pulse named *duration* is introduced. It is arbitrarily calculated by substracing the current timestamp with the last timestamp. Based on a list of *all* durations (also those that occured outside the episode), the possible upper and lower frequency of the qubit are chosen within an episode. This allows for the organism to have a memory of all durations it ever encounted, enabling it to map a duration to a frequency on the musical scale, based on its relative position in the overall duration memory. Whenever a pulse occurs, its duration is appended to a list of *current durations*. The list is sorted, and the position of the new value within it now represents a relative position within musical frequencies. Of that mechanism specifically, only the information is taken, whether a duration is new all-time low or high within the episode, to set the upper or lower note, based on the value being sorted into the list of *all durations* and its relative position in the list being mapped to the available musical scale.

This makes it possible for the system to, if it only ever encountered pulses of mostly "long durations" like with background radiation, to not know about the existence of shorter durations. It will play the durations it knows about within the full musical scale possible with Q1Synth for as long as it encounters durations that do not signifficatnly differ. If it then happens to be exposed to an environment with significantly higher radiation, its knowldge is expanded by the knowledge of even shorter possible durations. It would now deem the previously shortest duration to represent a note of lower frequency. This effect weakens over time. Assumed it would stay in a situation of higher radiation for a longer amount of time, the accumulation of more and more similar durations within the overall duration memory would lead to the musical scale tending more and more to represent the full scale for durations of the current situation of radiation level.

To summarize, The MIDI-Notes that Q1Synth is able to play were mapped onto a musical scale, and the lower or upper frequency is set according to the relative duration of a pulse.

Because of the limitation of **4** Qubits, they were grouped together into a larger *meta-episode* consisting of 4 single episodes. This meta-episode represents the relationship between 4 experiences made.

To create a meaningful compositional pathway, first of all the possible frequencies of each qubit need to be chosen so that they together create a harmonic chord. For that, whenever the upper or lower frequency of a qubit is set, it is ensured that the frequency can build a chord with the frequencies of the all previous qubits. This is done using pytuning, by calculating the frequencies corresponding to the note and octave that is about to be set. If the frequency already has occured, it will first try to build a chord with a third factor, depending on if it is a lower or upper boundary, in lower or upper direction. If the resulting frequency has again already occured, it will step further in the same direction in alternating factors of fifths and thirds until frequency is found that is not already present. This enforces the generation of a harmonic chord (a tetrad) as the last qubit of a meta-episode is measured, leaving it open to the model, to create unexpected harmonies that might share similarities other than the notes in use, but still represent a similar situation.

As an optional artistic choice, during the measurement of the last qubit, the previous three qubits can produce their sound in parallel.

To represent entanglement in a meaningful way, each qubit is entangled to its precessor with a CNOT-gate, meaning that if the result state of the previous qubit is $|1\rangle$, only then the state of of the current qubit is flipped. This gives the imaginary organism a way of taking a decision based on a previous experience, and a way to tell if a relationship between them exists or not. This takes place within within a meta-episode, no entanglement takes place in between meta-episodes.

For a representation of half-life, the values of the general reverb and delay are set for the qubit, according to the count accumulated in an episode. For that, all counts are remembered, so that if an episode occurs with the most count that ever occured, the longest delay and reverb are set, for it would represent a material with a higher half-life.

5 Conclusion

A meaningful approach has been discovered to interweave the introduced concepts and attribute significance to the input geiger counter pulses, forming a connection to a quantum entity in the form of a quantum circuit that generates music. This connection enables the audialization of the concepts and their effects, offering an educational tool for understanding them.

Notably, the model for an imaginary quantum organism showcased here exhibits properties akin to a human composer with memory. As the organism encounters diverse experiences throughout its lifetime, it accumulates knowledge about its environment. Consequently, depending on the context in which it resides, the organism interprets new information and groups episodes of its life into unique “memories” (measurements), each time in a different way than it would have before.

A compositional technique employing entanglement is presented, representing choices made over alternative pathways — analogous to decisions an individual organism could make based on its experiences and interpretable in terms of the many-worlds interpretation of quantum mechanics. The substantial variance in geiger counter pulses, and the very high precision of measured timestamps achieved through an interrupt-based implementation, allows for a broad spectrum of musical pathways to be explored, even more so if more dramatic changes would occur in the environment. The resulting composition is influenced by these experiences and choices, and this influence is reflected in the form of a repeated build-up of a chord with four entangled frequencies — “quantum harmonies”.

5.1 Limitations and outlook

- A mechanism for highlighting the difference in true and pseudo randomized input values could be implemented, that tests the input for true statistical randomness, and according to that produces a different sound.
- The possibilities for the sound that a measured qubit can produce are right now harmonic tones. This could be exchanged for samples of a quantized musical piece, or possible pathways based on a repertoire of a certain musical style.
- For now, rhytm is not taken into consideration, while it could be easily achievable by mapping notes onto a quantized grid, in which the notes are repeated based e.g. on the duration of the episode.
- Other parameters of Q1Synth could be used to e.g. make a more noisy sound for an episode that contains more variance in radiation.
- For now only the release is controlled to represent half-life. The actual behavior of exponential decay could be implemented by introducing an additional recording and playback instrument into the chain, that records the sound at the time at which they occur, in order to repeat them and decay the volume of each repetitions to resemble the decay of an accumulated amount of radiation.

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