INTERACTIVE SONIFICATION OF 2D QUANTUM SYSTEMS

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ABSTRACT

This paper presents novel sonification methods for the auditory representation of 2D quantum systems and their temporal evolution, encompassing examples such as the tunnel effect, single and double slit interference or behavior of light or matter in a given potential function. The simulation involves numeric integration of the Schrödinger equation. The sonification is based on three paradigms: (a) scanning the probability amplitude along a 1D-manifold (i.e. curve) as a waveform, (b) probing the probability amplitude as spectral activation along a 1D-manifold, (c) traversing the full 2D field as an audification. We illustrate the methods with sonification examples, discuss what can be learned about the behavior of quantum systems in non-stationary transitions and propose application scenarios in physical, musical and educational contexts.

1. INTRODUCTION

Quantum physics revolutionized the world over the past 100 years. Today's products such as LED lights, solar cells, atomic force microscopes and many others would be impossible without an understanding of systems down to the quantum level [1]. Yet philosophically, quantum theory disrupted a number of concepts deeply ingrained in our minds, such as that any object, no matter how small, would have a clearly defined location at any time. Quantum physics instead postulates an intrinsically probabilistic notion of reality, with many different frameworks for interpretation. The particle-wave duality is one of the essential conundrums observed in quantum physics, and the ability of single electrons to interfere with themselves when radiated one after the other through a double slit is mind-blowing, particularly as that individual electron is later sensed as a particle on the screen. With this disruptive change, "it becomes crucial to develop methods to make quantum physics and technology understandable for society" [1]. While mathematics allows to describe and model the phenomena with incredible accuracy, it can feel too abstract to fully grasp what is going on. "We have no *experience* of quantum phenomena [...]. Therefore, educating intuition needs imagination" [1]. Maybe adding sound (which lives in waves and time) in the form of sonification [2], to extend and augment a system's visualization, helps to gain deeper insight into quantum systems.

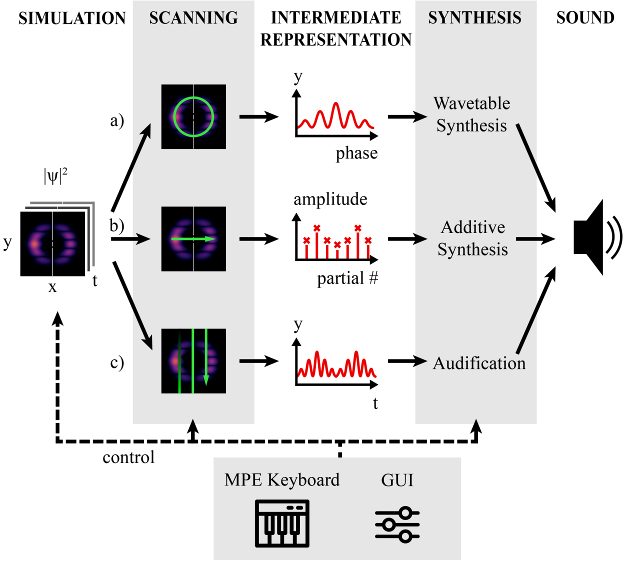

Figure 1: System Diagram of *QSynth2*. a) Path of Interest, b) Frequency Mapping, c) 2D Field Audification.

With this motivation, we expanded on an initial 1D quantum simulation used as a synthesizer (*QSynthi* [3]) towards a broader examination and exploration of how sound can help to discover or understand phenomena that normally unfold at the timescales of femtoseconds – such as switching on a light source in front of a double slit. Usually we only perceive the stationary pattern and can't perceive how a systems gradually converges to that state. However, with numerical simulations of quantum systems we can freeze time and control it in slow-motion.

Let's start our tour through an audiovisual quantum world in two spatial and one temporal dimension with reviewing the underlying physics (Sec. 3), introducing sonification concepts to probe systems auditorily as they unfold (Sec. 4), and looking – after seeing how to implement such ideas in software (Sec. 5) – into handpicked examples from an electron in an harmonic potential, tunnel effect, single and double slit experiments and more (Sec. 6). The tour will lead to extensions that make the sonification methods applicable to any other simulation with the same dimensionality, and generalize to sonification of cellular automata. Most importantly, the implementation allows for highly interactive real-time sonification and interaction. Furthermore, it offers opportunities be-

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yond scientific inquiry, such as novel sound synthesis techniques for musical instruments, or to support use cases in the monitoring of physical experimental settings. As to an evaluation, we conducted a qualitative study involving a few experts, and report their feedback.

2. RELATED WORK

An early contribution that contains a combination of quantum systems and sonification is [4]. A system of multiple particles and their interaction is simulated, but far below real time, which makes user interaction in creating sounds very difficult. The sonification does not use the actual quantum wave function, but rather the kinetic energy of the quantum object, which is put in a sine function to create a representation of the matter wave. The result of a musical composition with simulation and sonification is viewed as a "unique and successful musical language, [which] provides insight into the similarities of Art and Science" [4]. This paper aims to expand the ideas to incorporate real-time interaction and sonification of a quantum wave function.

A numerical simulation of the Schrödinger equation in 1D space is done by [5]. There, the time evolution of a quantum object in its wave function representation is put into an infinite square well. The particle's momentum is turned into sine waves of different frequencies that are added and produce moving sounds as the momentum changes. The resulting sounds are described as "attractive from a melodic and rhythmic perspective" [5]. Like in [4], the probability distribution is not sonified, but here it is displayed as a visualization. The article also discusses sound artifact prevention and mitigation, which provides a good overview of caveats to take into account.

In [6], the software application "QHOSYN" is presented, which uses the simulation of a one-dimensional space containing a quantum wave function. Finding "sonic potential in this physical model" is stated as a goal for the work, therefore multiple sonification methods can be selected and compared. In an outlook, it is also stated that "real-time user interference in the wave function's evolution" could be valuable, but requires different numerical simulations than the one used [6]. The implementation of multiple interchangeable sonification methods and live user interaction are interesting aspects that this paper explores.

3. QUANTUM PHENOMENA

With scales approaching quantum physics, classical physics and its concepts are not applicable anymore. At this scale, physical objects like particles can be in superposition where they show wave-like behavior which collapses when measured. Therefore quantum mechanics describes particles not as localized objects but by a complex-valued scalar field known as the wave function $\psi(\vec{x}, t)$, with $\vec{x} = (x, y)$ in 2 spatial dimensions. This wave function has no direct or tangible physical meaning, it is used by physicists as a versatile tool for calculations. However, the probability of detecting a particle at the position $\vec{x}$ when measuring the system is given by $\|\psi(\vec{x})\|^2$, i.e. the squared magnitude of its wave function [7].

This can be seen as a special case of the scalar product of the state with the observation operator O, i.e. $\langle\psi|O|\psi\rangle$ in bra-ket notation. For measuring the position, O is the Dirac $\delta(\vec{x} - \vec{x}_0)$ which is only non-zero at location $\vec{x}_0$. Generally, upon measuring a variable (e.g. the energy), the system collapses into the superposition of eigenstates of the measured observation operator for that value [7].

Prior to measurement, quantum systems exhibit wave-like behavior, leading to characteristic interference and diffraction patterns. This behavior is governed by the time-dependent Schrödinger equation, which describes the time evolution of a quantum wave function. The equation consists of two parts, one for the inherent kinetic energy of a quantum object and one for the influence of an external potential. In its most simple, dimensionless form it can be denoted as

$$i\frac{\partial}{\partial t} \quad = -\nabla^2\psi + V(\vec{x})\psi, \tag{1}$$

where $-\nabla^2$ represents the kinetic energy part (derived from $E_{kin} = \hat{p}^2/2m$, omitting units) and $V(x)$ is an arbitrary potential (e.g. electric potential), which could result in an attractive or repulsive force, or also appear as a barrier or barrier with slits. The latter ones result in well-known phenomena like quantum tunneling and single/double slit interference. A particular potential employed in our setup is an elliptic paraboloid. Analogies to understand the effects of this potential are an electron trap or atomic tweezers. A particle is pushed back to the point of the lowest potential (the vertex), with force increasing in the square outwards from the vertex. Influence on a quantum mechanical wave function is similar, as the probability density is "pushed" back when propagating outwards. This parabolic potential allows us to keep the wave focused in space, and repeatedly move e.g. through a double slit. This creates unique interference patterns and also exhibits other effects like quantum tunneling.

To enable interactive exploration of all the above-mentioned phenomena and effects, a numerical simulation is employed to solve the Schrödinger equation on a discretized 2D grid of complex values, similar to [8]. This grid $\phi_t(\vec{x})$ represents the quantum system at a given time t, hereafter referred to as a simulation frame. A split-step Fourier method is applied to efficiently compute the wave function's evolution over time [9], balancing computational efficiency and accuracy (see Figure 2). The formula used is

$$\phi_{t+\Delta t}(\vec{x}) = \mathrm{iFFT}\Big(e^{-i\,\vec{k}^2\,\Delta t}\;\mathrm{FFT}\Big(e^{-i\,V(\vec{x})\,\Delta t}\;\phi_t(\vec{x})\Big)\Big), \tag{2}$$

where $\phi_{t+\Delta t}(\vec{x})$ is the discrete wave state after performing a time step Δt, and $\vec{k}$ is the vector of wave numbers for each axis in momentum space (analogous in audio processing to converting the time series to the frequency domain, doing processing and converting it back).

The simulation is performed at a resolution of 128 × 128 grid points. The 2D space can be visually displayed in a video to show the time evolution, serving as an overview of the probability "flow" in the quantum system. It was chosen not to work with absolute physical units, because we don't investigate a concrete example, but a system that is applicable for different particles at different scales (e.g., atoms, electrons, photons). We set periodic boundary conditions for the simulated space (wrapping left to right and top to bottom), so that we obtain the topology of a torus. This is common practice for finite-size simulations to avoid boundary effects. Different from reality, in our simulation we can measure, plot and visualize the quantum state without collapse, and in turn sonify its temporal evolution.

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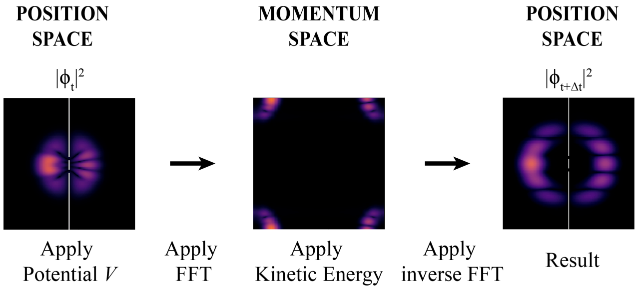


Figure 2: To compute the next simulation frame, i.e. the result of applying a discrete time step Δt to the 2D grid $\phi_t(\vec{x})$, the energy parts are applied separately, with a 2D FFT between them. These steps are also visible in the discretized Equation 2.

4. SONIFICATION CONCEPTS

The underlying data of the simulation has 2 spatial dimensions plus time, also called (2+1)-dimensional [8], which is similar to video data. While not trivial, there are already plenty of approaches that sonify this kind of data [10] [11]. As audio signals are only one-dimensional, many of these approaches scan the data along a path to reorganize the 2D data into one dimension [12] [13] [14]. The following three approaches all do this in a different manner to produce the sound.

Since this paper is not only about a measurable stationary outcome of these quantum systems, but about the process of getting there, it is important to keep the time dimension of the simulation as the time of the sonification. Normally these processes happen in the scale of femto- or attoseconds and are impossible to perceive by humans. Therefore, the simulation has to be played back several orders of magnitude slower than reality.

4.1. Path of Interest

The first sonification method involves scanning and interpolating the probability amplitude along a 1D-manifold called the path of interest. The sampled 1D data is then used as a waveform for a wavetable synthesizer [15] which can be played with a user defined rate (i.e. frequency in Hz), resulting in the perception of a tonal sound of a particular pitch [16, p. 41–62]. The time-varying data is thus contained in the repeating waveform and its evolution over time, which becomes audible in the (variations in) timbre.

The Path of interest could be chosen arbitrarily (arbitrary 1D manifold). However, two considerations are important to avoid obstructive artifacts, that are shown in Figure 3:

(i) The path should be chosen so that the value of the simulation at the start point equals the value at the endpoint. With repeated scans, differences between the endpoints cause sudden jumps in the waveform, resulting in harsh harmonics that mask the important information in the signal, even with small differences between the start and end values [16, p. 41–62]. One way to avoid this is to take a circle or another closed 1D trajectory as path of interest. An alternative is to perform a fore-and-back scanning. As the simulation (which has periodical boundary conditions if no artificial bounds are added) is topologically a torus, a straight vertical or horizontal line from one end to the other is topologically also a circle and thus also avoids these artifacts.

(ii) The path should be as simple as possible, because if it contains finer spatial details, these details are also reflected in the audio signal as finer details than the simulation, which can also lead to masking artifacts.

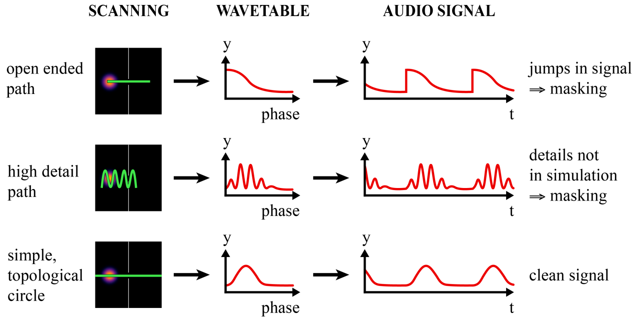


Figure 3: Examples for choosing a path of interest. The upper two choices introduce high frequency content in the audio signal leading to frequency masking. The third choice avoids both issues as it is simple and a topological circle, which follows from the fact that the simulation is a topological torus.

Although there are many sophisticated algorithms to better represent certain information while reducing the dimensionality of the data (e.g., [10], [13]), the path of interest has some key advantages. First, the concept is easy for users to understand, and second, it can be presented visually, making it clear which parts are sonified and which are not. Sampling the often relatively short path of interest at audio rate provides high temporal resolution of a given region, compromising spatial coverage to capture fast temporal features of the simulation, allowing for high simulation playback speeds.

4.2. Frequency Mapping

So far we have used the quantum field along the path of interest as a waveform (which is conceptually reminiscent of audification [17]). Frequency mapping, on the other hand, makes a different connection between a path of interest and its sonic representation: A fixed number m of points along the path are sampled over time and the observed values determine the intensity of a partial of an additive synthesis model [16, p. 204–209]. For instance, choosing partials as integer multiples of a fundamental frequency results in strictly periodic sounds at fixed pitch, hereafter referred to as *timbre mapping*, exhibiting timbre variations according to the quantum dynamics. Specifically, spatial movement now corresponds to movement in timbre. This approach requires additional user parameters, such as the number of harmonics n, or whether the points should be linearly or exponentially distributed along the path of interest. For practical reasons we apply an A-weighting, i.e. roughly a -6 dB/octave slope over partial frequency to roughly balance the human ear's sensitivity bias towards higher frequencies.

As said before, the n points can be sampled along the path of interest with different spacing: The easiest approach is to sample the points with equal distance for an even distribution on the path of interest. However, clearer results could be achieved when the points are sampled with exponentially decreasing distance as the perceived pitch interval of the individual harmonics decreases with higher harmonics. This is due to the fact that JNDs (just-noticeable differences) of pitch decrease with frequency. An exponential mapping to frequency is therefore equivalent to a linear mapping of location to pitch [16, p. 41–62].

4.3. 2D Field Audification

The previous approaches focus on a region of interest. In return, they discard information in non-represented regions. Some form of information loss is inevitable when reducing dimensions of continuous data, but in our case the underlying data, i.e. the numerical simulation, is discrete. Therefore, it can be flattened by appending all lines or columns together, similar to how the electron beam of a cathode tube television sequentially covers the screen by a row-by-row scanning for each frame (mechanically achieved using a Nipkow disk). The resulting stream of values can then be played as audio.

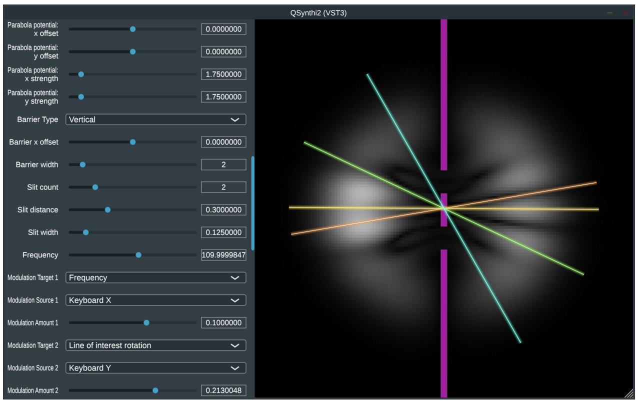
A grid size of 128 × 128 results in 16384 samples, which would make up for about 0.37 seconds of audio with a sample rate of 44100 Hz. The sample rate can be adjusted to change the playback duration of each frame, which also alters the pitch. While playing more simulation frames per second is desirable to better perceive temporal changes of the simulation as rhythm, it increases the pitch, using less of the audible frequency spectrum and losing details above the highest frequency (e.g. 10 kHz for elderly users) [16, p. 41–62]. This requires a compromise between playback speed and pitch. Playing 3 to 8 simulation frames per second was found to be a reasonable range.

However, the idea of sonifying all the data without loss is not feasible in practice. Interesting scenarios of the simulation, like one pass through the double slit, is simulated in hundreds, sometime thousands of time steps. If all generated simulation frames are sonified in succession, the resulting audio would take minutes, which is too slow for our “sweet spot” timescale to notice differences [16, p. 63–85]. Therefore, some kind of stride has to be introduced, skipping either time steps, rows or columns. This enables shorter durations when only sonifying each n-th time step and lowers pitches when skipping rows or columns as the total number of audio samples per simulation frame decreases. In the end, it is again a trade-off between temporal and spatial resolution versus coverage, which is best balanced by knowing the underlying data.

5. IMPLEMENTATION

We implemented the sonification concepts within a Jupyter notebook for prototyping and systematic analysis. The numeric simulation was implemented heavily leveraging `numpy` performance benefits since the simulation data quickly gets in the range of hundreds of megabytes with a spatial resolution of 128 × 128 and several hundred time steps per second required for accurate results. The sonification was implemented using the three-dimensional `numpy.ndarray` from the simulation. The results were then rendered into a video with sound track using the `ffmpeg` multimedia editing tool.

While Jupyter notebooks are excellent for interactive development and prototyping, it is not easily possible to interact with the simulation or sonification in real time as the notebooks effectively do an offline-rendering of the whole result. Therefore, we (re-)implemented our system as an audio plugin *QSynth2* (see Figure 4) using the framework `JUCE`[1]. The software is available as a Virtual Studio Technology (VST) and AudioUnit (AU) plugin and thus can be loaded into almost any Digital Audio Workstation (DAW). It can then be controlled with a standard MIDI keyboard but also with a MIDI Polyphonic Expression (MPE) keyboard for additional control.



Parabola potential: x offset	0.0000000
Parabola potential: y offset	0.0000000
Parabola potential: x strength	1.7500000
Parabola potential: y strength	1.7500000
Barrier Type	Vertical
Barrier x offset	0.0000000
Barrier width	2
Slit count	2
Slit distance	0.3000000
Slit width	0.1250000
Frequency	109.9999847
Modulation Target 1	Frequency
Modulation Source 1	Keyboard X
Modulation Amount 1	0.1000000
Modulation Target 2	Line of interest rotation
Modulation Source 2	Keyboard Y
Modulation Amount 2	0.2130048

Figure 4: Screenshot of the *QSynth2* GUI, with a parameter list (left) and a display area for simulation and sonification (right). Here, four notes are played that sonify different parts of the simulation space symbolized by the different colored paths of interest. Their rotation is offset as a result of a per-note modulation using a ROLI-Seabord (MPE keyboard).

We designed a modulation system similar to [18], where modulation sources can be mapped to any parameter at runtime directly from the plugin GUI. Modulation sources can be external, such as MIDI controllers, and internal, such as envelopes and low frequency oscillators (LFOs). Sources do not have to be mapped directly to a parameter, but can control the depth of other modulations, allowing for modulations of any depth. It also supports MIDI Polyphonic Expression (MPE) controllers, allowing e.g. the modulation of each individual note based on the x and y position of the finger on the key. Rather than imposing pre-defined interaction mappings, our system allows users to determine which parameters they wish to explore in depth or use in live performances. An example modulation setup can be seen in Figure 4. Not only the sonification parameters, but also the simulation parameters such as barrier position or playback speed can be altered while the simulation is running. It can be slowed down, stopped completely, and even reversed to revisit events of interest and replay them, perhaps with slightly different parameters, without having to restart the simulation from scratch. This allows the user to interactively control and examine the simulation, which has great advantages for scientific and educational purposes [19], as well as for musical uses of the sonification, far beyond the capabilities of our predecessor project (*QSynthi* [3]).

As mentioned above, the simulation requires extensive performance requirements. With performance-oriented libaries like `Eigen`[2] it is possible to run the simulation in real time on mid-range devices at the time of writing. However, with the way audio plugins request audio samples for only a few milliseconds in advance, computing the required simulation time steps just-in-time is not possible as it results in undesired cracks in the audio. Therefore, the simulation is computed in parallel on a separate thread

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[1] `https://github.com/juce-framework/JUCE`

[2] `https://eigen.tuxfamily.org`

where it can run independently from the audio processing. While this means much more effort in the implementation, the separate thread also allows for a separate buffer just for the simulation of about 50-100 ms. This makes it more resistant to performance spikes caused by other software running on the device, while keeping the latency low enough for real-time interactivity, especially since all other systems like the sonification aren't affected by this extra latency.

The implementation is realized with clear separation of the main components – simulation, sonification and modulation system. The separation is achieved using encapsulation, so the only dependency shared between the components is the data to process. Thus, a component can be easily replaced or reused in other projects. For example, this opens up the possibility of extending the contexts beyond the Schrödinger equation and quantum mechanics by applying the proposed sonification and modulation methods for different simulations. The source code is publicly available on GitHub[3].

6. AUDITORY EXPLORATIONS

To see and hear the simulation in action, 4 scenarios have been chosen that show distinct quantum behavior. Some hand-picked simulation frames of the key moments of each scenario are shown in Figure 5. The scenarios are sonified using all three sonification methods with identical settings for each scenario, resulting in a 4×3 matrix of examples. One example of each scenario is explained in more detail, where the applied sonification method was found to be particularly suitable for that scenario. While all examples were rendered using a Jupyter notebook, most of the insights that led to these structured examples were gained using the interactive audio plugin. Because all parameters can be tweaked in real time through a GUI rather than through code, settings were explored that we would not have explored through code. Also, the process of fine-tuning for desired interference patterns and sounds is much faster.

The 12 examples can be found in the supplementary material[4] as audio and video files, with the simulation displayed together with the selected path of interest. The Jupyter notebook used to generate the examples is available on GitHub[5]. The number of the example represents the simulation scenario, and the letter represents the sonification method used.

6.1. Harmonic Oscillator

The first scenario, the quantum harmonic oscillator, is one of the first examples of quantum physics that physics students learn as an analytical tool. In this example, a parabolic potential is set with its lowest point in the center. The wave starts from a position of high potential and therefore gains velocity towards the lowest point. After passing this point, the kinetic energy is converted back to potential energy and the process starts again, resulting in a harmonic oscillation, similar to a classical pendulum.

Example 1a: Here, the probability density is sonified using the path of interest audification with a circular path shown in green in the video. When the wave touches the circle, a tone with the selected frequency of 100 Hz can be heard. Consequently, no sound is produced when the wave is in the center of the plane. Since the farthest point of the wave's oscillation is slightly beyond the radius of the circle, a slight increase in volume can be heard when the sound is about to stop and just after the wave reverses direction.

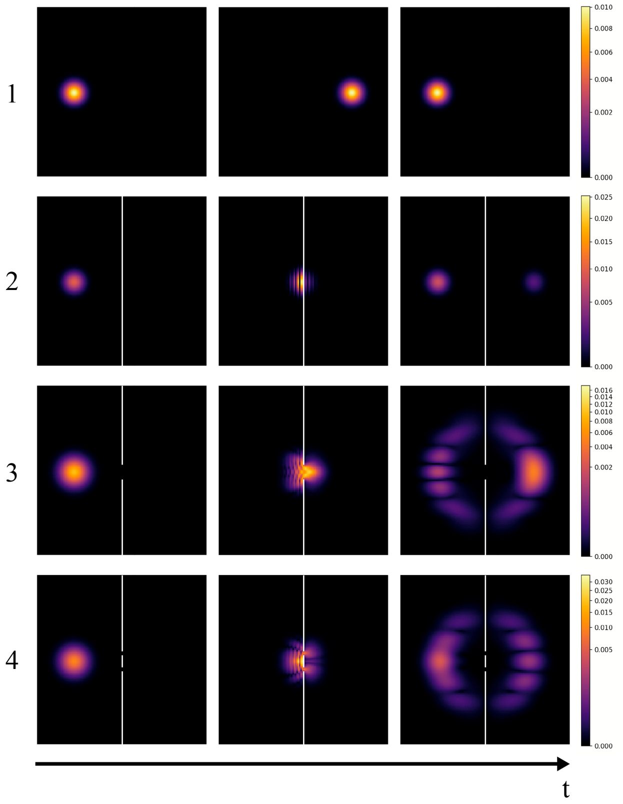

Figure 5: Some hand-picked simulation frames of key moments for each of the four selected simulation scenarios: 1) Harmonic Oscillator, 2) Quantum Tunneling, 3) Single Slit, 4) Double Slit.

Example 1b: Here, the probability density is sampled at 16 points along the line of interest mapped to the amplitude of a tone's partials. The amplitude of the lowest frequency is sampled at the start of the arrow, while the highest frequency is sampled at its tip, so the arrow points toward increasing frequencies. These points are distributed with logarithmic decreasing distance so the movement of the wave is proportional to the movement in pitch.

Example 1c: This is a Field Audification where the plane is scanned column by column from top to bottom and from left to right. A spatial stride of 4 is used, i.e. only every 4th column and every 4th cell of a column is used for sonification. In this way, a reasonably low pitch could be achieved while playing back 8 simulation frames per second. Consequently, a stationary wave would result in 8 identical "blips" per second. As the wave moves in or against the direction in which the columns are scanned, this frequency increases or decreases depending on its velocity. If the simulation was scanned line by line instead of column by column, this effect would be much less pronounced, since the horizontal distance would not correspond to such a large temporal distance in the sonification. In any case, the sound of an individual blip remains constant, due to the constant shape of the wave in this particular example. If the potential became stronger or weaker, the

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[3] `https://github.com/arth3mis/qsynth2`

[4] `https://doi.org/10.4119/unibi/3003278`

[5] `https://github.com/jannosch/qsynthi_prototyping`

wave would become narrower or wider when passing the center point. This would be audible as a change in the timbre of each individual blip. The resulting rhythm in the sound of this example is not only considered a pleasing property of sound [20], but is also easier to interpret for people with no or little musical experience, compared to the difference in pitch, as pitch is often confused with timbre and volume [16, p. 41–62].

6.2. Quantum Tunneling

Quantum tunneling is the ability of quantum particles, such as electrons, to pass through barriers that would be considered impenetrable for that particle in classical physics. This means that the particle has a small probability of being found on the other side after a collision with a wall. As computer chips get smaller and smaller, this has to be taken into account in the design of the chips, because electrons can jump between the physically separated wires, causing errors in the computation. Therefore a good understanding of this effect is necessary.

The simulation is set up identically to the harmonic oscillator simulation, but a thin wall of extremely high potential is placed in the center. When the wave hits the barrier, a small portion of it tunnels through the barrier to the other side. Since the parabolic potential is still applied, the wave is then accelerated back to the wall, leading to repeated collisions. After many collisions, one might intuitively assume that the probability would even out on both sides of the barrier, since the wave on the other side would tunnel back to the original side. This is not the case here, instead the particle tunnels through the wall completely before starting to tunnel back after several collisions with the wall.

Example 2a: Here the probability density of the simulation is sonified, identical to example 1a, with a circular path of interest. Initially, the sound is the same, but as some of the wave tunnels to the other side, the timbre changes accordingly. Eventually, when there are equal parts of the wave on both sides of the barrier, the sound becomes an octave higher in time because there are now two identical peaks in the waveform per oscillation.

Example 2b: With equal timbre mapping settings to example 1b, but with the barrier introduced, all content at the left side of the barrier corresponds to the lowest partials while the right side corresponds to the upper partials. As the wave gradually passes through the barrier, the amplitude of the higher partials increases while that of the lower partials decreases. Because the splitting wave is Gaussian shaped, the resulting sound consists of two formants that move up and down in frequency with varying intensity. The sonification is set up so that these formants are roughly in the range of the formants of the human voice. This allows the sonification to produce vowel-like sounds[6] [16, p. 278–279]. This similarity to the human voice is a very desirable property in sonification. Because sound cannot be pointed at like images, it is often more difficult to talk about a sonification than to talk about a visualization of the same data. The ability to reproduce sound with the human voice addresses this problem and enhances the ability to talk to other people about sound. Additionally, our ears are highly attuned to interpret vocal sounds, which was also utilized in [21].

Example 2c: Like in example 1c, the initial single wave starts out as a single blip sound. With the field audification set to scan column by column as the wave splits, the number of blips also doubles, with different volumes according to the wave size. The timing changes as the waves move relative to each other, with the blips directly behind each other as the two peaks are close together and equally spaced in time as their distance is half the simulation width. Also, when the waves hit the center, a distinct impact sound can be heard.

6.3. Single Slit

Another special property of quantum particles mentioned earlier is particle-wave duality, where a particle exhibits wave-like behavior such as interference with itself. This occurred to some extent in the previous example, but becomes really apparent when slits are introduced into the simulation. Again, the simulation is set up identically to the previous example, but this time a single slit is introduced in the barrier through which the particle can pass.

Often, these simulations are rendered just after the wave first hits the barrier to examine the resulting interference pattern. However, since this work is focused on gaining a general understanding of the wave's behavior rather than analyzing the static result of a few realistic experiments, it was decided to run the simulation beyond this point. Therefore, the wave repeatedly collides and interacts with the single slit and interferes with itself, resulting in increasingly complex patterns. To not obscure these patterns the simulation was setup to minimize quantum tunneling. Also it was decided to play this and the following simulation at half the speed of the above simulations because more detail in space and less long term relationships can be heard than in the previous examples.

Example 3a: Here, the single-slit experiment is sonified using the circle of interest audification. The circle is set up to include not only the interference pattern behind the slit, but also the reflections from the wall. As the interference patterns become more complex, the timbre becomes more complex, and vice versa.

Example 3b: When the single slit is sonified with timbre mapping, the resulting interference patterns will not be captured due to the placement of the line of interest. If the interference patterns are of interest, a different scanning path could be chosen, such as a semicircle on the right side of the slit. Since the examples are intended to present a variety of other interesting properties to be sonified, the focus in this configuration is on how much of the wave travels to the other side and how much is reflected. Note that with this wide single slit, a high proportion of the wave travels to the other side, while only small amounts are reflected.

Example 3c: This example demonstrates very well how the different variables we humans think in, like velocity and (wave) shape, are represented in different sound qualities. While the movement of a wave is encoded in the rhythmic speed, the distance between two parts of the wave is encoded in the relative timing of the blips. If the two parts of the wave are close together, the two blips will sound immediately after each other, and vice versa. The spread of the wave along the x-axis is represented by the blip length, while the shape on the y-axis, which is where the interference patterns spread out the most, is represented by the timbre. Thus, while this sonification method includes information about the greatest number of wave properties, it also presents the user with the greatest amount of auditory information to comprehend, especially as the number of sonified simulation frames per second increases. Therefore, we see the potential for this approach to be particularly well suited for the blind community, who have the incredible ability to process auditory information quickly, as also utilized in [20] and [22]. However, more research is needed

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[6] When transcribing the interviews where the timbre mapping sonification was set up similarly to this example, the transcription software identified the sonification as a separate speaker saying simple words like "wow".

to confirm this. At the same time, the results of the interviews suggested that the high information density might lead to a high entry threshold for physics students or other people unfamiliar with sonification.

6.4. Double Slit

Now we come to the finale – the famous double slit experiment. In our simulation, this is realized by adding a second slit to the barrier. The result is the well-known interference pattern on one side, but also the reflected part, which is most often neglected. In the accompanying Jupyter notebook[7] you can experiment with different interference patterns by changing the position and width of the slits. As with the single-slit example, the parabolic potential is still applied, which accelerates the waves back towards the center, leading to a sequence of collisions and more and more complex interference patterns.

Example 4a: When comparing the sonification of the double slit configuration to the other scenario with the circle of interest audification, a more complex timbre is immediately apparent. This is due to the more complex interference patterns of the double slit. Since one of the secondary goals of this project is the musical use of the synthesizer, this is where it gets interesting. In several sessions with Gregory Kramer playing the synthesizer, he saw a lot of artistic potential in this configuration, which results in a rich timbre that evolves over time. In this context, audible patterns, such as the 2-cycle pattern of structured and diffuse waves heard in this example, are not only useful from a sonification point of view, but also from an artistic one.

Example 4b: The timbre mapping sonification of the double-slit experiment, focused on the horizontal lines, sounds very different from the single-slit example. While in the previous example the path of interest passes directly through the slit, no impact sound was audible. With the double slit, however, there is now the center part of the barrier, resulting in an audible impact sound. Since the two slits are smaller in total than the rather large single slit, more of the wave is reflected, resulting in a more "wow"-like sound than in the tunneling example.

Example 4c: When sonified with the field audification, the impact noise becomes even more dominant. The 2-cycle pattern is also clearly audible. The blips after the first impact are much more diffuse compared to the single-slit example, which makes sense since the double-slit configuration produces more complex interference patterns.

7. DISCUSSION & CONCLUSION

This paper presents novel methods for sonifying quantum systems and their temporal dynamics, focusing on real-time interaction and multimodal representation. The proposed concept and implementation allow users to intuitively engage with complex quantum phenomena, such as tunneling and interference patterns, through visual and auditory feedback. We conducted expert interviews to receive initial qualitative insights and practical feedback.

Gregory Kramer, founder of the ICAD and pioneer of the sonification scene, emphasized the immediate, interactive sound response of the system and highlighted the artistic and insight-enhancing value of real-time parameter manipulation, especially the ability to reverse simulation time. While powerful, the parameter manipulation could benefit from a more intuitive GUI and predefined presets to reduce cognitive load and make the system more accessible to novices. Furthermore, several sonification configurations produced aesthetically pleasing sounds, suggesting potential applications beyond scientific contexts, particularly in musical and artistic domains.

Yunxin Ye, a Physics PhD student experienced in quantum systems and music, found the sonifications intriguing but hard to comprehend without prior familiarity. When comparing audification and timbre mapping, she expressed a clear preference for timbre mapping due to its melodic qualities and easier interpretability. Audification, while perceived as more monotonous and initially more difficult to interpret, also revealed interesting auditory features directly related to quantum phenomena, such as distinct sounds indicating barrier crossing. In addition, Ye emphasized the benefits of combined visual-auditory displays, noting that visualizations help contextualize auditory cues and vice versa, although she also noted that simultaneous processing requires initial adaptation and practice. She suggested that temporarily disabling one modality could help users better understand and process the information individually, ultimately benefiting the overall learning experience.

Both the experts and the authors found it preferable to play the simulation at a higher speed than is typical for visual analysis. Auditory perception excels at capturing and remembering sound details because rapid audio playback allows rhythmic patterns to be more effectively retained in short-term memory, making it easier to compare successive events.

A technical evaluation demonstrated that our modular implementation is robust, highly responsive, and extensible. The modularity facilitates adaptation to other simulations or physical models, significantly broadening potential applications.

From a musical perspective, *QSynth2* provides reproducible, deliberate, and engaging sonic results, creating unique opportunities for musical expression and live performances, especially when paired with visualizations. These musical attributes extend the utility of the tool beyond educational purposes, potentially bridging artistic creativity and scientific exploration.

Future developments should focus on enhancing usability through improved GUI and preset configurations, allowing users to benefit from intuitive interaction. Expanding the physical scope of simulations to other wave-based systems and equations could further increase versatility, making the system applicable to a broader range of scientific and educational contexts.

In conclusion, our methods effectively combine interactive sonification with 2D simulations, offering novel approaches to sound synthesis and an alternative, multimodal experience that could help learners understand quantum mechanical phenomena. The developed tool (*QSynth2*)[8] has great potential across musical, scientific, and educational applications, warranting further exploration and development.

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[7] `https://github.com/jannosch/qsynthi_prototyping`

[8] `https://github.com/arth3mis/qsynth2`

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