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"Beyond Quantum Music"—A Pioneering Art and Science Project as a Platform for Building New Instruments and Creating a New Musical Genre

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Abstract: In this text, we discuss the "Beyond Quantum Music" project, which inspired pianists, composers, researchers, and innovators Sonja Lončar and Andrija Pavlović (LP Duo) to go beyond the boundaries of classical and avant-garde practices to create a new style in composition and performance on two unique DUALITY hybrid pianos that they invented and developed to create a new stage design for multimedia concert performances and establish a new musical genre as a platform for future musical expression. "Beyond Quantum Music" is a continuation of the groundbreaking art and science project "Quantum Music", which began in 2015; we envisioned it as a long-term project. In order to build an experimental dialogue between music and quantum physics, we created the DUALITY Portable Hybrid Piano System. This innovative instrument was essential for expanding the current sound of the classical piano. As a result, new compositions and new piano sounds were produced using various synthesizers and sound samples derived from scientific experiments. The key place for this dialogue between music and science was the Delft University of Technology, the Netherlands, where Andrija Pavlović, as a Kavli artist in residence, and Sonja Lončar, as an expert, spent several months in 2022 collaborating with scientists to compose new music. Later on, we collaborated with the visual artist "Incredible Bob" to develop the idea for the multimedia concert "LP Duo plays Beyond Quantum Music" to be performed at various locations, including the Scientific Institute MedILS Split (Croatia), the Theater Hall JDP Belgrade (Serbia), the Congress Hall TU Delft (the Netherlands), and open-air concerts at the Kaleidoskop Festival (Novi Sad, Serbia) and Ars Electronica Festival in Linz (Austria).

Keywords: art and science; quantum music; hybrid piano duo; new musical instruments; DUALITY Portable Hybrid Piano System; original compositions for two hybrid pianos; new musical genre; multimedia performance

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1. Introduction

In this article, we wish to explore the concept of applied research in the domain of music[1] by presenting our own work at the intersection of performance, composition, scientific research, and technological innovation. We will discuss the groundbreaking art and science projects "Quantum Music" and "Beyond Quantum Music" and explain how we went beyond the boundaries of classical and avant-garde practices in order to create something new and original.

Art and science have interacted throughout the history of music. Pythagoras (c. 570–c. 495 BC) founded the order of Pythagoreanism, which sought to unite the fields of art and science, music and mathematics (Huffman 2024). (Figure 1). Three fundamental elements of Pythagorean music theory are closely related to his name: the mathematical analysis of music, the idea of musical ethos, and the psychagogic and educative impact of music. Pythagoras is credited with developing the classical Western musical scale that is still used today (Britannica 2024). Additionally, he believed in the concept of the

"Music of The Spheres" (Birat 2018)[2], which posits that the movements of celestial bodies such as planets and the Sun and Moon create a harmonious, musical symphony. Many scientists throughout history have been influenced by music or have considered music and musical patterns to be a component of the (natural) sciences. Plato (427–348 BC) valued the ethical dimensions of music, while Johannes Kepler, the German philosopher, astronomer, mathematician, and musician (1571–1630), wrote a book titled "Harmonices Mundi" in 1619 that discussed the harmony of geometrical forms and natural phenomena. In the modern era, Jacques Attali has famously asserted that music has always been connected to society and the advancement of new technologies (Attali 1977). On the other hand, many composers were inspired by nature and science. To name just a few examples, Gustav Holst (1874–1934) wrote the orchestral suite "The Planets" between 1914 and 1917, and avant-garde composer, architect, and mathematician Iannis Xenakis (1922–2001) applied the concepts of mathematics, statistics and physics to create his musical compositions such as Pithoprakta (1955–1956), where he used the statistical mechanics of gases.

Figure 1. (Pythagoras: "Music is mathematics").

Today, one could say that Western art music has become stagnant and needs to realign with 21st century breakthroughs. But, can 21st century science help music to evolve now? And, if yes, how?

Quantum physics was our inspiration for the creation of new, original music of the 21st century. It inspired us to expand the sound of the classical piano, creating the innovative instrument DUALITY Portable Hybrid Piano System. Additionally, the microscopic world and scientific experiments also provided a foundation for the creation of new sound banks, a VST quantum instrument, new original compositions, and a specially developed multimedia concert entitled "LP Duo plays Beyond Quantum Music."

But what did the journey that brought us to this point look like?

2. LP Duo as an Embodiment of a Hybrid Duo (Quantum Pianists and Composers)

For the last 20 years, as members of the LP Duo (Lončar/Pavlović), we have experimented with various possibilities of playing on two pianos (Lončar and Pavlović 2018, p. 111).[3] In addition to the classical repertoire that we learned during our undergraduate and specialist studies at the Faculty of Music, University of Arts in Belgrade, and afterward, at Hochschule für Musik und Theater Rostock (Germany), where we completed Master's and Konzert-examen (KEX) studies for piano duo, since the very beginning of our careers, we have been interested in contemporary art—performing works by contemporary composers, collaborating with artists from the domains of visual and applied arts (video art, film, photography, performance, dance, theatre), playing in ensembles and bands covering different genres (rock, popular, experimental music), and playing different types of synthesizers.

After a successful debut at Carnegie Hall in 2014, we felt that we needed a new challenge in our career. At that time, our long-term collaborator, sound designer, and acoustician Prof. Dr. Dragan Novković (School of Electrical and Computer Engineering,

Academy of Technical and Artistic Applied Studies in Belgrade) and his high school friend, quantum physicist Prof. Dr. Vlatko Vedral (University of Oxford and the National University of Singapore), met after more than 20 years and started to talk about a possible new collaboration that would study the relations between quantum physics and sound.

After their invitation, we began brainstorming ways to bridge the gap between the seemingly distant worlds of quantum physics and music. They invited us due to our extensive artistic backgrounds, which include diverse projects in various disciplines and genres, as well as our expertise as skilled producers. Artistic curiosity, combined with a thirst for new knowledge and creative freedom, led us to the realization of the pioneering art and science project "Quantum Music" (2015–2018). This project has since evolved into "Beyond Quantum Music" (2019–2022), pushing the boundaries even further. Both projects were funded by the European Commission (program Creative Europe) and coordinated by the Institute of Musicology of the Serbian Academy of Sciences and Arts. For details on these projects, see Medić (2022b).

3. Quantum Physics as a Playground and Inspiration—"Quantum Music" Project, Beginnings

Quantum physics is one of the most exciting and rapidly developing scientific fields today. Quantum mechanics deals with the behavior of matter and energy on a very small scale and has led to the development of many advanced technologies; as such, it has the potential to transform our understanding of classical physical phenomena and significantly impact our lives.

In 1923, Louis de Broglie, a French physicist, proposed his theory of matter waves, which suggested that particles could display wave-like properties and vice versa. His theory had a profound impact on our understanding of matter and energy and laid the foundation for the development of quantum mechanics. Later, in 1959, Richard Feynman, an American physicist and Nobel Prize laureate, introduced the concept of nanotechnology, which deals with manipulations of matter on the nanoscale level. Since then, nanotechnology has emerged as a field with the potential to revolutionize many areas of science and technology, including electronics, materials science, and medicine.

But how do sound and music intersect with these core scientific disciplines? In theory, if our ears were small enough, we could hear the sounds of the quantum world. However, in reality, this is not possible, as the sounds of the quantum world are beyond the range of human hearing. Nonetheless, the results of experiments conducted in these fields can be used to synthesize sounds and create new musical compositions. This has led to the emergence of a new genre of music known as Quantum Music, which incorporates the sounds and concepts derived from quantum mechanics.

Bose–Einstein Condensate (BEC) and Sounds of the Quantum World

The world of sound, which we experience every day, and the world of quantum physics, which lies beyond our sensory perception, may seem like two entirely separate domains. However, there is a fascinating intersection between these two worlds in a specific area of quantum physics.

In 1925, two renowned scientists, Albert Einstein and Satyendra Nath Bose, predicted that matter cooled to extremely low temperatures would exhibit unique and unspecific characteristics. They named this state of matter a special name—condensate. This discovery has opened up exciting possibilities for understanding the fundamental properties of matter and has potential applications in various fields, including physics, engineering, and computing. Named after these two scientists, this state of matter, now called the Bose–Einstein condensate (BEC), was first achieved in a famous 1996 experiment which was later awarded the Nobel Prize (The Nobel Prize in Physics 2001). Since then, laboratories around the world have created this state of matter, using ever-more sophisticated experimental equipment that allows for highly precise analysis of this newly formed state.

The condensate is the fifth and least-known state of matter in addition to gas, liquid, solids, and plasma. Each gas at temperatures close to us implies the movement of atoms,

which is very chaotic and disordered (known as Brownian motion). Each atom behaves like a system in itself, with defined energy states and modes of vibration, based on which it interacts with other atoms in the environment. When atoms are cooled down, all the atoms in the system move to the lowest possible energy state (Novković et al. 2018, p. 97). Scientists describe atoms as having both corpuscular and wave properties. As the temperature continues to decrease, the frequency of vibrations in the atoms decreases, while their wavelength as waves increase. At temperatures close to absolute zero, the wavelengths of atoms become so large that the waves from individual atoms overlap and the atoms start behaving like one quantum system. This state, in which groups consisting of millions of atoms begin to behave like one system, suggests that the entire universe may be a single quantum system, which is on the borderline area of today's science explaining that, in fact, everything is interconnected.

Acoustics defines sound as a mechanical wave that occurs in an elastic medium. In experiments, the state of the condensate can be analyzed in different ways after it is reached. One classic way is to excite it with a laser beam, causing a change in density in certain parts of the condensate. This change is transmitted through the Bose–Einstein condensate (BEC) as a mechanical wave in an elastic medium, which is the definition of sound. In the condensate, which is described by its quantum properties and is subject to the laws of quantum mechanics, a sound wave is generated.

Quantum Acoustics is the field of quantum physics that studies this phenomenon. It represents the intersection of two incompatible worlds. From this starting point, the idea of Quantum Music began to develop. It is a project that aims to answer questions about the relationship between sound and music on one hand and the quantum world on the other. Also, the idea of the project was to present the concepts, experiments, and phenomena of quantum physics to a wider audience through a unique multimedia concert for two specially constructed DUALITY Portable Hybrid Piano Systems.

In the first years of the project (Quantum Music, 2015–2018) we worked on the Bose–Einstein condensate experiment, creating sound banks to be used for the first newly composed, original works as well as compositions by other composers that we arranged for a specially produced European multimedia concert tour in 2017.

For this project, sounds have been generated based on the BEC's experiment and theory using two methods. The University of Aarhus in Denmark conducted successful experiments in Quantum Acoustics which we used for the "Quantum Music" project with the help of Prof. Dr. Klaus Mølmer. Due to our direct access to the laboratory and the results of Quantum Acoustics experiments, Dragan Novković used MATLAB software[4] to convert these results, which were presented in graphical and tabular displays of changes in acoustic pressure over time, into sound (Novković et al. 2018, p. 101). Surprisingly, the frequencies of sound waves generated in this experiment were in the range of human hearing. This unexpected situation allowed us to make direct translations, comparisons, and interpretations of the quantitative and qualitative properties of quantum-acoustic and acoustic waves without needing any additional scaling.

The second category of sounds that was created was the result of applying mathematical formulas that simulated the energy state of a condensate. The process of condensation results in a release of energy that can be modeled using mathematical equations; by manipulating these equations, it is possible to generate a wide range of synthetic sounds[5] that are unique and interesting (Novković et al. 2018, p. 102). These sounds can be used for various purposes, including music production, sound design, scientific research, and to compose new musical compositions or arrange compositions by other composers during the project.

4. DUALITY Portable Hybrid Piano System—Innovative New Musical Instrument

We have taken gradual steps to achieve a milestone—the invention of a new instrument, the DUALITY Portable Hybrid Piano System (Figure 2),[6] that would become the main tool for our compositional and performative artistic life.[7]

Figure 2. (DUALITY Portable Hybrid Piano System).

DUALITY is a blend of a traditional acoustic piano and an electronic instrument, offering infinite possibilities to create new sounds and explore new artistic spaces. The goal is to continue pushing the boundaries between classical and contemporary music.

What were the obstacles and inspirations that led us to make DUALITY?

Through years of research into analog, digital synthesizers, and MIDI technology, we investigated the endless possibilities of sound. As pianists, we explored the sound possibilities of the piano and imagined how certain parts of compositions would sound on other instruments (Pavlović 2018; Lončar 2018; Lončar and Pavlović 2018). Even in early music school days, we were taught to imagine how specific parts would be played by different instruments from the orchestra, helping to improve our imagination, listening skills, and exploration of the piano's sound. The digital synthesizers were less interesting due to their pre-prepared sound banks that lacked inspiration and possibilities. However, the first analog synthesizers[8] that we encountered, the KORG MS-20 and Moog Opus 3, allowed for sound alteration in many different ways. Creating sounds on analog synthesizers using potentiometers and cables on a patch field created an organic sensation resembling sound creation on an acoustic instrument. We were captivated by the diverse range of sounds and colors this synthesizer could produce, and it took countless hours of practice and experimentation to understand how even the smallest adjustments to its potentiometers or modular cables could impact its sound. In many ways, playing these instruments was reminiscent of playing pianos, requiring a level of sensitivity and precision that only acoustic instruments could match. With oscillators that can be controlled independently, analog synthesizers are capable of producing an even wider array of sounds and possibilities. While the control parameters were different from the piano, we found that the number of parameters available was the most similar to playing an acoustic instrument. Despite some of them being monophonic and having only three octaves, analog synthesizers have provided us with so many opportunities to pursue and explore their capabilities for years to come. Our journey with these instruments led us to discover other synths, including modular, analog, and semi-digital ones such as JUNO 60, Moog Polymoog, A-100 Analog Modular System, Minimoog, Yamaha CS-15, ARP Odyssey, and many others.

Soon we began to arrange various contemporary and classical compositions for analog synthesizers. However, due to the limitations of these instruments, we needed at least seven or eight synthesizers to perform the planned repertoire at concerts. As we used original instruments dating from the 1970s and 1980s, they were prone to frequent breakdowns. During concerts, certain functions would be canceled multiple times, forcing us to improvise on the spot. But, even when faced with various challenges, we never let them get in our way. For years, we continued to use the same instruments because they produced sounds that matched our creative vision and gave us the ability to shape the sound in real time, just like we would on a piano. But, there were even more challenges in front of us.

Certain compositions that were extremely virtuosic, such as Ligeti's (György Ligeti) compositions for harpsichord[9], were very complicated to perform on these instruments. The plastic keys on these synthesizers were not designed for such precise and virtuosic playing. We thought about connecting the analog synthesizers to some other keyboards, but due to the lack of MIDI technology on these old instruments, it was not possible. To solve this problem, we researched MIDI software and used keyboards with hammer mechanics to perform all the compositions. However, we always fantasized about playing analog or MIDI sounds on a real piano keyboard, which would be the perfect instrument for us.

There was another problem that was only partially solved over time. We often found ourselves longing for acoustic sound after a certain amount of time in the electronic sound "jungle", and we believed that our audience felt the same way too. The sound of an acoustic piano was something that was missing the most. Soon we started playing a combination of acoustic pianos and synthesizers at concerts. Initially, there were some technical difficulties with synthesizers, but we overcame them by arranging certain parts for pianos. The combination of acoustic and electronic sound became a perfect hybrid setup for us. With this "hybrid setup," we were able to implement all the arrangement and compositional ideas adequately.

Furthermore, we often encountered a problem when switching from one instrument to another during performances. In certain setups where we were surrounded by synthesizers stacked on and around the piano, it became challenging to make a perfect arrangement of synthesizer positions. Different compositions required synthesizers to be used with either the left or right hand while the other hand played the piano. It was sometimes impossible to make a comfortable and practical arrangement for all compositions. Besides the issues with virtuosity, we also considered the idea of performing everything on a single keyboard that could quickly change sounds. The only perfect keyboard for us has always been the piano keyboard. Our experience in preparing the piano and the desire to overcome technical shortcomings in performance gave us the initial idea for "digital" piano preparation. In this way, the idea of a perfect instrument for us was born and, in the following years, DUALITY was created.

DUALITY is a revolutionary instrument that blends the traditional sound of an acoustic piano with the versatility of a digital synthesizer. It is a unique combination of analog and electronic worlds. The first magnetic prototype that we worked on at the beginning of the "Quantum Music" project had certain limitations, such as difficulty in installation and transportation. Furthermore, it was not easy to insert on certain types of piano, and the time required for installation was too long.[10] To address these challenges, LP Duo collaborated with engineers from HTEC, an American company, during the follow-up project "Beyond Quantum Music" to develop the final prototype, with optical sensors placed above the piano keys; we named it DUALITY.[11]

The DUALITY is a state-of-the-art instrument with 88 optical sensors, one for each piano key, placed above them. Each sensor can detect the slightest movement of the key, providing an accurate and responsive playing experience. The optical sensors allow for a more user-friendly design, making it easier to install and transport. The analog controls of the DUALITY enable the player to enjoy both acoustic and digital sounds in real time, resulting in a unique and dynamic listening experience. The system can be easily connected to the computer or music program (DAW) via a USB cable and used as a sound or light controller. After a brief calibration sequence, users can leverage their preferred VST instruments to produce stunning sounds.[12]

5. Beyond Quantum Music (2019–2022)

In the second "Beyond Quantum Music" project, which was a continuation of "Quantum Music," the main place of experiments was the University of Technology Delft in the Netherlands. There, we had the opportunity to spend three months working with scientists from the Quantum Nanoscience, Bio Nanoscience, and Qu-Tech departments (Medić 2022b).[13]

The first part of the residency involved regular meetings with the scientists, listening to them discuss their work, visiting labs, and learning about the principles of their research. We drew inspiration from these conversations and the scientific data that we found. Following this, we began composing in our improvised studio, located in the Quantum Nanoscience department.[14] The studio was equipped with an old, abandoned upright piano called "Tchaika" from the 1980s, which we obtained from a nearby second-hand shop. This piano was "prepared" with the DUALITY instrument. Additionally, we used an electric Nord Piano 4 as both a piano and MIDI controller, a hi-fi system, an eight-channel mixer, two sound cards, two microphones with stands, and all the necessary cables to connect everything.

In addition to the guest scientist from Denmark, Prof. Dr. Klaus Mølmer from the Niels Bohr Institute in Copenhagen, we have developed special collaborations with Prof. Dr. Sander Otte and Prof. Dr. Kobus Kuipers from the QN Quantum Nanoscience department, Assistant Professor Eliška Greplová from the Quantum Meter and A.I. department, and Dr. Dimphna Meijer from the Bionanoscience department. The collaboration took place both theoretically and in the laboratory.

VST Synthesizers: The Development of the New "Quantum Modal Scale" Series

During the Kavli Artist in Residence program at TU Delft, LP Duo collaborated with the Danish quantum physicist Prof. Dr. Klaus Mølmer to create a new musical scale based on expanding the harmonic order of the basic tone in equal temperament on the piano. Mølmer was inspired by the regular and irregular frequencies of molecules, investigating the number of their modulations that could reflect certain quantum properties.

The VST Quantum Synthesizer (Figure 3) introduces a new tuning system that deviates from traditional Pythagorean logic and is inspired by quantum mechanics to establish new harmonic connections. In Western music, the relationships between the fundamental tone and harmonics are based on a 3:2 ratio or a pure fifth, such as the octave (2:1), pure fifths (3:2), and pure fourths (4:3). This frequency relationship sounds harmonious and beautiful to the human ear because the harmonics of corresponding frequencies perfectly align.

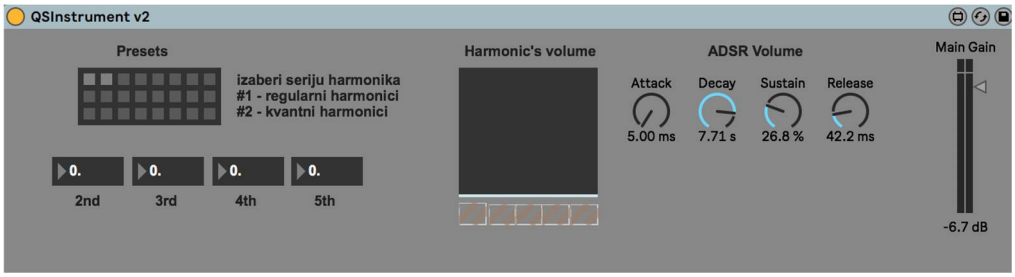

Figure 3. (VST Quantum instrument).

The VST Quantum Synthesizer introduces a new factor, represented as '*a*', which defines a new variable relationship between semitones. This factor amounts to $\boldsymbol{s^{1/12}}$, where **s** represents the harmonic.

In the traditional Pythagorean system, the octave is represented in a 2:1 ratio. In the newly established system, any value other than 2 can be chosen to obtain a new semitonal relationship. For instance, choosing the value 2.5 for a new octave, which is the second harmonic, results in a new semitone value of approximately 1.08006. Using this new value 'a', all 12 intervals of one scale can be calculated using the formula $f_n = f_0 \times (1 + a)^n$, where n represents the new interval and 0 is the fundamental frequency. For instance, in the case of an A tuning fork (440 Hz), the new octave (12 semitones) would be 1100 Hz, a pure fifth would be 646.68 Hz, etc.

The quantum piano system maintains harmony between intervals, similar to the Pythagorean system but with a more flexible approach to tuning and new scales. In the maxMSP loop, all harmonics of the quantum piano are obtained using the formula

mentioned above. This process allows the user to change the variable value '*a*' while the other values and intervals are automatically calculated.

6. Challenges

The "Beyond Quantum Music" project has been an ambitious undertaking from the start. Like any project of this scale, we have faced various challenges along the way that have tested our determination and creativity. At the outset of the "Quantum Music" project, the initial challenge was the substantial gap between the worlds of music and quantum physics. One of the main obstacles in such an interdisciplinary project is the disparity in language and communication styles between the two disciplines. Quantum physicists often use complex mathematical formulas and technical jargon to describe their work, while composers may approach their work from a more subjective and artistic perspective. Bridging this gap requires both parties to make an effort to understand each other's language and terminology. This may involve providing explanations and analogies to ensure that both parties comprehend each other's perspectives. Frequent communication and open dialogue are essential to ensuring that each party's ideas and contributions are properly understood and incorporated into the project. We have observed that the majority of scientists utilize artistic language to explain scientific theories, often using linguistic and literary metaphors, stories, and occasionally images. In some cases, they may even incorporate sound and music. As a result, we have discovered a shared language between the realms of creativity and imagination.

All of the discussions with physicists were meticulously captured in recordings. These invaluable recordings formed the basis for the creation of music for the multimedia concert "LP Duo Plays Beyond Quantum Music." Rather than simply turning the sounds into music using mathematical formulas and synthesis, we aimed to use the conversations and experiences as inspiration for entirely new and original musical compositions.

Another obstacle in the collaboration between composers and quantum physicists may be the differing timelines and work processes of the two disciplines. Quantum physics research can be a lengthy and complex process, while composing music requires a different creative timeline. To address this challenge, it was helpful to establish clear timelines and milestones for the project, as well as interim reports, to ensure that both parties were progressing in tandem.

We successfully overcame all challenges through open communication, mutual respect, and a willingness to learn from one another. By embracing the unique perspectives and expertise of both disciplines, we were able to create an innovative and groundbreaking work that combined the beauty of music with the complexity of quantum physics. However, the "Beyond Quantum Music" project faced financial difficulties, largely due to coinciding with the COVID-19 pandemic. Consequently, several activities, including a competition for artistic works intended for exhibitions in Belgrade and at the Ars Electronica Linz Festival, as well as a multimedia European concert tour of LP Duo, had to be postponed for a year. Additionally, our partner, the TodaysArt Festival from The Hague, withdrew from the project due to bankruptcy. This prompted us to quickly find new partners, and we successfully collaborated with our colleagues from the MedILS Institute in Split, Croatia. Following a successful concert by LP Duo at the Ars Electronica festival in Linz, a presentation and discussion with the audience were organized the next day.[15] The audience response was fantastic, and we received many questions. However, we also encountered a negative tone aimed at downplaying certain aspects of our project. With patient dialogue and openness, we were able to explain to the discussion participants the method and freedom inherent in our artistic work, which was inspired by quantum physics.

7. A Comparison to Similar Projects

Globally, there are similar projects exploring the convergence of quantum physics and classical music as well as the development of new keyboard instruments. One such endeavor is the "Sounding Qubits"[16] project led by Professor Eduardo Miranda, a Computer

Music expert at the University of Plymouth (UK). The project was showcased at the Goethe-Institut London on 8 December 2022. This interesting work explores the possibilities of composing and performing pieces together with quantum computers. By programming these devices operating at a subatomic level, Miranda has unlocked a diverse range of sound banks, establishing a direct connection with A.I. for live performances, creating a compositional process and musical results that are unpredictable. This adds a new dimension to music, blending sonification with the fundamental principles of quantum physics, where the qubit represents the basic simultaneous values of zero and one.

The "Beyond Quantum Music" project takes a different approach. It utilizes sonification and sound banks as the foundation for composing new electro-acoustic compositions, primarily tonal or those merging tonality and experimental music, thus remaining faithful to the essential principle of establishing harmony.

The "Magnetic Resonator Piano" (McPherson 2018) project shares some similarities with our "DUALITY" hybrid piano instrument through the use of optical sensors positioned above the piano keys. This innovation reflects a concept previously explored by the renowned company Moog, which was later abandoned for undisclosed reasons. The "Magnetic Resonator Piano" employs additional hardware and electromagnets placed above the piano strings to induce independent vibrations, enabling the piano to sustain sound continuously for as long as necessary, akin to string instruments controlled by a bow or wind instruments regulated by breath (McPherson 2018).

In contrast, our "DUALITY" hybrid piano addresses this issue digitally. It enables the piano to connect to any computer or digital device via USB, providing unparalleled possibilities for digital sound preparation with VST instruments or audio samples. Moreover, by pressing a key gently, one can silence the sound of the piano, allowing the digital synthesizer or any other sound to be heard. This offers the option of using the piano as a synthesizer, with sound that can be sustained indefinitely.

8. On the Genesis of Compositions for the "LP Duo Plays Beyond Quantum Music" Multimedia Performance

During the work process, we wrote several new compositions (*Intro, Scanning Tunneling Microscope, Rogue Waves, Silence, Qubit Funk*) and rearranged a few of our older compositions (*Mayday! Mayday! Mayday!, Collapse, Between the Waves* and *Lemon, Honey, Ginger*).[17]

The important part of the audio–visual performance was a specially written poetry by LP Duo that was performed by two AI voices, "Brian" and "Amy". This ingredient gave a special, emotional feeling to the audio–visual performance. In all compositions, "Amy" and "Brian" "played" along with us and became an integral part of the performance, as they were prerecorded, and we used their voices as music samples in the Ableton music program. These voices poetically presented certain concepts and phenomena from the quantum world and compared quantum principles with the issues facing our modern society.

8.1. Intro

The entire electronic sound is based on altering harmonics and establishing new scales derived from specific molecular states, i.e., quantum systems observed and arranged into harmonic sequences by Klaus Mølmer. The composition mirrors, metaphorically, the processes of birth, molecule movement, and quantum-state fluctuations.

Sonja gently opens the piece on the synthesizer, as "Brian" narrates the poetry:

> "All around you see beautiful phenomena, nature, galaxies, flowers, waterfalls, rainbows, and a lot of these physical phenomena are described by the same concepts and ideas. But when we move down to the very microscopic scale, to the atoms, which are, after all, actually what makes up everything in our world around us, Life is different, Things are different, Reality is different."

Then, Andrija begins to play a simple delayed melody on top of the music material using the VST Quantum Instrument. The "Intro" starts seemingly from nowhere and ends up fading into nothingness.

8.2. Mayday! Mayday! Mayday!

In this composition, the philosophical question of reality was explored. What is reality? Does it truly exist? Does it only exist when it is observed? The father of quantum physics, the Danish Nobel prize winner Niels Bohr, formulated this in the following way: "Everything we call real is made of things that cannot be regarded as real". This composition is made for two DUALITY instruments. The piece starts with a grand baroque-style opening, followed by Sonja's use of an arpeggiator synthesizer while Andrija plays groovy chords. "Brian" also plays an important role here, narrating the text:

> "Reality does not exist. What we perceive is a small part of reality. Reality is what you choose to observe. Reality does not exist if you are not looking at it. 'Everything we call real is made of things that cannot be regarded as real' (Niels Bohr)".

8.3. Scanning Tunneling Microscope

In this composition, we collaborated with a scientist and jazz music enthusiast, Prof. Dr. Sander Otte, at the University of Technology Delft, on the "Scanning Tunneling Microscope" experiment. In his lab, we had the unique opportunity to directly capture the sound of atoms. We recorded the tunneling current[18] from the probe tip of the microscope to the sample surface and amplified that signal. The tip and the sample are almost touching, but not quite. The gap between them was in the order of 500 picometers, or about two atom diameters. At that distance, according to quantum mechanics, electrons can "tunnel" through the vacuum barrier. This results in a current, which we can measure. When the tip touches an atom to move it, the current suddenly spikes, resulting in a sound when amplified. We used this recorded sample as a part of the composition. Together with Sander, a passionate lover of jazz piano, we used harmony Cm7 (9/11) and built the composition from that material (in the chorus part we are using following harmonies: Cm7, A-flat major 7, Fm7, D-flat major 7). The entire composition is based on two counterpoint parts. The opening features the sounds of atoms and VST synths, creating a cold and deep atmosphere of the microscopic world that Andrija breaks with a rhythmic bass line and piano patterns, joined later by Sonja. The piece gradually builds up to a climax before returning to the opening theme at the end of the composition.

8.4. Rogue Waves

Prof. Dr. Kobus Kuipers, a quantum physicist and head of the Quantum Nanoscience department, inspired us to combine two concepts that he has worked on into one composition. The first concept is the slowing down of light, which occurs when light passes through silicon. The second is the phenomenon of giant waves that appear suddenly, without warning. The composition is rhythmically based on the delay assigned to Andrija's hybrid piano, creating periodic waves that build the material of the composition, evoking huge waves.

In *Rogue Waves*, "Brian" recites the following poetry by LP Duo: "Quantum physicists are slowing down the light. Becoming slower, we are energetically efficient. Becoming slower, that is a struggle. Rogue Waves are unusually large, unpredictable and suddenly appearing surface waves that can be extremely dangerous".

The text "Extremely Dangerous" is repeated throughout, similar to the composition "Scanning Tunneling Microscope", where there is a comment about "atoms being manipulated" (which is indeed the case in the experiment). However, figuratively speaking, is this what happens in the microscopic world an analogy for the repression and control in today's societies?

8.5. Collapse

This composition was developed from the previous pilot project Quantum Music (2015–18), and the title refers to the Bose–Einstein Experiment (BEC).

When a particle is not observed, it lacks a defined position and size, existing everywhere simultaneously. To represent this concept, we created quantum sound samples using additive synthesis based on equations of motion of the observed particles provided by Prof. Dr. Klaus Mølmer. The process of sound synthesis based on theoretical equations was conducted following the principles of additive synthesis, realized using Java Script and Max MSP software. The synthesis of sounds based on the results of experiments was achieved using MatLab software by Dragan Novković.

The composition consists of three parts. The first part begins in a baroque style with large chords and a developing melody being played rhythmically by Sonja's arpeggiator and Andrija's jazzy piano part. The middle part of the composition includes experimental improvisation.

Here, "Amy" starts to speak: *"Without anybody to observe it, a particle does not have a well-defined position or velocity. We can only guess where it is, and how fast it is going. It is everywhere at once, traveling at all speeds. The only way to localize a particle is to observe it. And when we close our eyes, once again only the wave of probabilities remains. But, how do we know that things are like that? How do we know what's going on when we are not looking?"*

The third and final section of the composition is characterized by minimalistic patterns that are dynamically "driving us" towards the end of the piece, culminating in a single powerful chord that brings the music to an abrupt halt.

8.6. Silence

The most poetic composition *Silence* is related to the whole concept of Quantum Music and the idea that "silence" is actually identical to the concept of "quantum vacuum". The process began by recording a "deaf room" (studio office F333 at TU Delft) for several hours. When the volume was turned up, we were surprised by what could actually be heard there.

This "silent tape" served as the basis for a composition that emerged "from nothingness". "Silence is my quantum vacuum", "Zero point energy", "Music energy", and "Silence is my music" are just some of the poetic lyrics that "Amy", our artificial intelligence friend, interpreted. This composition is very romantic and has an almost "Schubertian" vibration coming from the sorrowful top melody under which we placed harmonies of the most melancholic tonality—F minor.[19]

8.7. Between the Waves

The concept of duality[20] in quantum physics refers to the phenomenon of a particle also existing as a wave. Waves are a significant source of energy, and matter is believed to be both a particle and energy simultaneously. Duality serves as a way to reconcile conflicting phenomena.

Our composition "Between the Waves" is featured on our album "Dead Sea" (Universal Music 2022). For the "Beyond Quantum Music" project, we have expanded the piece by adding the first movement titled "Marvelous Forms of Energy". In this movement, Sonja performs on the Rhodes piano synthesizer while Andrija manipulates and resamples Brian's voice.

> "Waves are marvelous forms of energy.
>
> Waves transfer energy from one place to another without transferring matter.
>
> The matter is a wave and a particle at the same time.
>
> Two contradictory pictures of reality, separately do not explain the phenomena of the quantum world, but together they do.
>
> This is called the wave-particle duality.
>
> Duality, Duality, Duality, Duality
>
> Waves/Particles, Waves/Particles"

The second part of the composition "Between the Waves" remains unchanged from the original. The bass sample slowly flows beneath the sounds of pianos and synths, leading effortlessly towards the dramatic theme in pianos towards the end of the piece.

8.8. Qubit Funk

For this composition, we collaborated with two exceptional scientists: quantum physicist Eliška Greplová and bionanoscientist Dr. Dimphna Meijer, both from TU Delft.

They began working together to study quantum systems, exploring connections with neural systems, cells, and molecules. Using quantum computers, the two tried to calculate and predict certain behaviors of neurons.

Eliška and Dimphna provided us with graphic explanations of these processes. Then, we imported data into the music program "Fruity Loops", generated images, and obtained a specific sound form from which we later composed a powerful bass line; on top of that, we added the following new elements: a repetitive, minimalist accompaniment that transitions into the funky groove of the *qubit*[21] and eventually concludes with a romantic and gentle atmosphere, symbolizing the fusion of man and machine, artificial and natural intelligence (this part is our little ode to Daft Punk).[22]

Throughout the entire composition, we incorporated the real sound of quantum computers that we recorded at TU Delft's "Qu-tech" department. By recording the quantum computers for hours, we were able to use their rhythm as the foundation of the composition.

8.9. Lemon, Honey, Ginger

This is one of our favorite compositions, also in F-minor; it begins with Andrija's chords on DUALITY, accompanied by "Amy"'s narration of these two quotes:

> "As more and more artificial intelligence is entering the world, more and more emotional intelligence must enter into leadership." (A quote by Amit Ray)
>
> "Success in creating AI would be the biggest event in human history. Unfortunately, it might also be the last, unless we learn how to avoid the risks." (A quote by Stephen Hawking)

The piece transitions into Sonja's piano part, which pays homage to pianist and composer Ryuichi Sakamoto (1952–2023). The second part gradually builds to a powerful, *forte* sound with both pianos playing together, creating an anthem-like chorus. The composition concludes with a calming return to the first theme, with "Amy" delivering the final words:

> "Humanism directs us to an ethics of care, a practice of care, the development of a compassionate temperament, and the importance of love and kindness." (A quote by Ken Plummer)

9. Production of the Multimedia Concert "LP Duo Plays Beyond Quantum Music"

In the first phase of the Quantum Music project (2015–2018), we collaborated with artist Lazar Bodroza, a designer and director from the "Metaklinika" studio in Belgrade. Together, we created a multimedia concert that aimed to illustrate the fundamental concepts of quantum physics through music and video projections. The concert featured original compositions such as "Interactive Quantum Installation", "The Birth of Quantum Particles", "Collapse—Ostinato for Leonid Sejka", "Good Morning, Mr. Correa", and "Teleportation". Additionally, we arranged pieces by other composers for two DUALITY instruments, including Chiel Meijering's "Rondo", Antonio Correa's "Maquina III", and Ivan Božičević's "Sustainable Development" and "Spring Passes".

For the "Beyond Quantum Music" project, we wanted to create a multimedia concert with a specific focus on scene and light design. To achieve this, we brought on board the talented visual artist and VJ, Miroslav Sretenović also known as Incredible Bob, who is a resident at the renowned Belgrade techno club, "Drugstore".

The visual part of the performance includes generic video content that follows the dramaturgy of the concert and the atmosphere of the compositions, enhancing them through

synesthetic experiences. The visual appearance of the projections was inspired by abstract patterns, particles, and liquid forms found in scientific experiments and visualizations of microscopic records of splitting atoms.

In addition to the video projection, visual artist Incredible Bob integrated an ILDA RGB laser to complement the stage design by synchronizing it with the video projection. The laser is mapped to outline the shapes projected by the video. Visuals are created using a GLSL shader and Quartz Composer.

In some compositions, cameras were employed to capture the musicians, and in the split screen, close-up shots of the piano keys and fingers were displayed during the projection. By doing so, we emphasized the duality and the human standing in front of the technology, adding an organic, humane element to the minimalist aesthetics of digitally generated content. The lighting design completes the atmosphere, emphasizing the relationship between the musicians on stage but also building dynamics in faster compositions. In addition to conventional lighting, the laser bars were also used to create a spectacular effect, intersecting and building networks and geometric forms.

Lighting design plays a crucial role in enhancing the atmosphere, highlighting the connection between the musicians on stage and creating dynamics in faster compositions. Alongside traditional lighting, we incorporate laser bars to create a visually striking effect, forming intersecting networks and geometric shapes.

10. Conclusions

Today, quantum physics is a prominent topic, with increasing dialogue and collaboration occurring between the fields of art and quantum physics. The main reason for this is the rapid advancement of quantum computing and artificial intelligence. When we started working on the "Quantum Music" project nearly a decade ago, it was considered a pioneering art and science project.

In our initial meetings with scientists, we had to bridge the gap between the worlds of quantum physics and music as well as navigate the different perspectives of being a scientist versus being an artist. During the "Quantum Music" project, we engaged in discussions to overcome initial misunderstandings. As a result, we successfully translated the language of quantum physics into sound and music. This allowed our creativity, a fundamental human quality, to bring us together and create a unique connection.

In today's world of very high-skilled specializations, we have chosen to embrace multiple roles as artists, researchers, innovators, composers and producers. While this requires significant time and energy to learn new skills, it also provides a broader perspective and experience that is essential for musical creation and expression. Maybe one of the reasons for that is that we started playing piano very early, at the age of 5, and so by our 20s we had proficiently developed this skill and could dedicate ourselves to other spheres of research (composition, science and other artistic disciplines).

Throughout our career, we have focused on transcending boundaries to create our own unique musical language that blends the opposite worlds of classical music and other genres. Quantum physics has played a crucial role in enabling us to achieve this. The microscopic world has served as a playground for our creation of the DUALITY instrument, new original compositions, and the new musical genre of "Quantum Music."

The "Beyond Quantum Music" project introduced new possibilities for playing the acoustic piano by incorporating the DUALITY hybrid piano. This innovative approach provides performers with an expanded palette of sounds and VST instruments, allowing for a seamless blend of acoustic and digital music. We anticipate that the DUALITY hybrid piano will eventually be integrated into music schools and conservatories, leading to a growing number of pianists embracing this innovative instrument. For the next generation of pianists, the DUALITY hybrid piano represents an exciting and creative form of expression. Both beginners and amateurs can benefit from the DUALITY hybrid piano, as it can help them cultivate a passion for playing and address technical challenges more effectively. The instrument itself contributes to new possibilities in composing classical

music of the 21st century. Boundaries between genres become blurred, allowing the entire history of music, both classical and popular, to coexist freely and without prejudice. In the long run, all of this contributes to the development of original classical music in the 21st century.

The project "Beyond Quantum Music" has offered us the chance to explore new sonic and musical experiments inspired by science. Discussions among scientists, artists, and musicologists bring up new fundamental questions for the future development of humanity. Quantum physicists and bionanoscientists have the opportunity to engage in conversations with artists, allowing them to immerse themselves in different processes of thinking and creation. Through the language of music and art, they can develop new skills, use analogies to communicate their scientific theories more easily, and gain fresh ideas for further research. Finally, the discussions between art and science promote creative thinking, stimulate imagination, and bridge the gap between natural and humanistic sciences.

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Notes

1 Once concerned predominantly with music's socio-political or performative contexts, applied musicology and other types of applied music-related research are nowadays very broadly conceived, interdisciplinary, and aimed at stepping outside of the academic 'ivory tower' and using their findings for the benefit of society at large. For recent accounts on applied musicology see Medić (2022a); Dromey (2024).

2 Also known as "Musica universalis" or "Harmony of the spheres" (Birat 2018).

3 Aside from playing an almost complete classical repertoire for piano with four hands and two pianos, we performed some of the most famous contemporary music pieces, e.g.,: Karlheinz Stockhausen's "Mantra" (1970) for two ring-modulated pianos, John Cage's "Three Dances" (1944) and "A book of music" (1944) for two prepared pianos, etc. Later on, as passionate collectors of analog synthesizers from the 1970s and 1980s, which we used mainly in popular music genres, we decided to make arrangements of several contemporary music pieces for these instruments (album "Mechanical Destruction" by LP Duo, 2016, Dansk Komponist Forening (DKF) & New Art Center, Belgrade). In the last phase, that anticipated the invention of the DUALITY Portable Hybrid Piano System, we performed concerts for two pianos and synthesizers (Live @ Studio 6, Radio Belgrade, 2016, https://www.youtube.com/watch?v=kekTyXQACrc, accessed on 24 July 2024).

[4] MATLAB is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

[5] This is called additive synthesis, which is a sound synthesis technique that creates timbre by adding sine waves together. The timbre of musical instruments can be considered in the light of Fourier theory to consist of multiple harmonic or inharmonic partials or overtones.

[6] From here onward, we will simply refer to it as "DUALITY". For additional photographs and videos of the instrument, see https://www.lpduo.com/duality/. Since 2016 we have successfully performed more than 70 concerts worldwide on these original instruments (Singapore, Paris, London, New York, Amsterdam, Salzburg, Linz, Barcelona, Belgrade, Split, Ljubljana, Skopje, etc.).

[7] LP Duo recorded an album "Duality" (Universal Music, 2019) with the original compositions for two DUALITY hybrid pianos. Link to the album: https://lpduo.lnk.to/Duality accessed on 24 July 2024).

[8] An analog synthesizer is a synthesizer that uses analog circuits and analog signals to generate sound electronically. The earliest analog synthesizers in the 1920s and 1930s, such as the Trautonium, were built with a variety of vacuum-tube and electro-mechanical technologies.

[9] We have arranged, performed, produced and published two pieces by Ligeti, "Continuum" (1968) and "Hungarian Rock" (1978), in the version for two Juno 60 synthesizers (album "Mechanical Destruction". For a live performance of theses pieces, see our concert at Studio 6 of Radio Belgrade: https://www.youtube.com/watch?v=kekTyXQACrc (accessed on 21 February 2024).

[10] The first prototypes of the future DUALITY were made during the first "Quantum Music" project together with engineers Darko Lazović and Dragan Novković. The devices were tested on many types of pianos and at LP Duo's concerts in 2017 and 2018.

[11] The project "DUALITY Portable Hybrid Piano System" was supported by the Innovation Fund of the Republic of Serbia (Innovation Fund 2020). This prototype was successfully developed, and today DUALITY is a step closer to being on the market (we are negotiating with different piano manufacturers and audio production companies to mass produce and sell this instrument worldwide).

[12] One of the noteworthy advantages of DUALITY is its effortless assembly process. It can be quickly installed on any upright or grand piano in just 15 min without requiring any physical interventions on the piano. Moreover, it is compatible with all types of pianos, making it a versatile solution for various piano models, regardless of the manufacturer. Another remarkable feature of the DUALITY system is its portability. It is the world's only portable hybrid piano system that can conveniently fit in a backpack, weighing under 200g, making it an ideal solution for individuals who travel a lot, like we do. It has been a game-changer for us and has allowed us to push the boundaries of what is possible during live performances.

[13] The project "Beyond Quantum Music" faced several delays because of the COVID-19 pandemic. In 2022, Andrija Pavlović was selected as Kavli Artist in Residence at TU Delft. He and Sonja Lončar spent three months in Delft researching scientific experiments and composing new music for two DUALITY hybrid pianos.

[14] Room F 333, building 22, TU Delft.

[15] This presentation was incorrectly announced in the festival program as the unveiling of the DUALITY hybrid piano instead of the "Beyond Quantum Music" project.

[16] For more information on the project Sounding Qubits, see: https://www.goethe.de/prj/lqs/en/eve/sou.html (accessed on 23 February 2024).

[17] These were taken from our albums "Duality" (2019) and "Dead Sea" (2022), Universal Music. See: https://www.discogs.com/artist/7992204-LP-Duo-Sonja-Lon%C4%8Dar-Andrija-Pavlovi%C4%87 (accessed on 19 February 2024).

[18] A tunneling current occurs when electrons move through a barrier that they should not be able to move through. In classical terms, if you do not have enough energy to move "over" a barrier, you will not. However, in the quantum mechanical world, electrons have wave-like properties.

[19] Hermann von Helmholtz, a German physicist, once described F minor as harrowing and melancholy. Christian Schubart, a German Romantic poet described this key as "Deep depression, funereal lament, groans of misery and longing for the grave" (Schubart 1806).

[20] Wave–particle duality is the concept in quantum mechanics that quantum entities exhibit particle or wave properties according to the experimental circumstances. It expresses the inability of classical concepts such as a particle or a wave to fully describe the behavior of quantum objects. See the lecture by Prof. Dr. Vlatko Vedral on the "Quantum Music" project (Vedral 2016).

[21] In quantum computing, a **qubit** (/ˈkjuːbɪt/) or **quantum bit** is a basic unit of quantum information—the quantum version of the classic binary bit physically realized with a two-state device. A qubit is a two-state (or two-level) quantum-mechanical system, one of the simplest quantum systems displaying the peculiarity of quantum mechanics. See https://www.quantum-inspire.com/kbase/what-is-a-qubit/ (accessed on 15 February 2024).

[22] Daft Punk was a French electronic music duo formed in 1993 in Paris by Thomas Bangalter and Guy-Manuel de Homem-Christo. They achieved early popularity in the late 1990s as part of the French house movement, combining elements of house music with funk, disco, techno, rock and synth-pop. Website: https://www.daftpunk.com/ (accessed on 5 February 2024).

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