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The Newness of Quantum Music

In this study, I discuss the diverse possibilities of interweaving quantum physics and music. After providing an overview of several recent, mutually different approaches to combining quantum physics and music, I describe two collaborative EU projects in which I was involved for seven years: "Quantum Music" (2015–2018) and its 'sequel', "Beyond Quantum Music" (2019–2022). I provide basic information about these projects, describe their artistic and scientific components, and highlight their innovativeness. In conclusion, I pose numerous questions about the feasibility of 'new music' in the 21st century and the very concept of 'newness', while highlighting how quantum music in its various incarnations can inspire us to think about the possibilities of kickstarting a new avant-garde. I conceptualise quantum music as a path to a new avant-garde that is tailored to the needs and challenges of the 21st century while retaining strong links with the past.

Introduction

In what follows below, I wish to present the diverse possibilities that exist for interweaving quantum physics and music and examine the different possible approaches to it. I also want to focus on a specific approach with which I was personally involved. I am referring to two EU cooperation projects that I led in the past seven years: "Quantum Music" (2015–2018), with partners from Copenhagen, Ljubljana and Belgrade and associate partners from The Hague, Aarhus and Hannover, and its 'sequel', "Beyond Quantum Music" (2019–2022), with partners from Linz, Split and Belgrade and an associate partner from Delft. I will provide information about these projects and highlight their innovativeness while offering an overview of other options for interaction between quantum physics and music. To conclude, I will attempt to answer certain pressing questions that go beyond the scope of these two projects and are at the very heart of contemporary music production and systems of consumption.

Since the turn of the millennium, there have been several attempts across the world to connect quantum physics with music. A collection of papers published in 1999 entitled *Language, Quantum, Music* provided a theoretical, conceptual and philosophical foundation for this endeavour while summing up the then "present state of research in all directions of Logic and Philosophy of Science".[1] An experiment conducted in 2006 in the American laboratory Fermilab to turn matter into antimatter[2] that was later confirmed experimentally in CERN[3] provided an idea as to how to explore the possibility of turning the resultant oscillations into sound.[4]

1 Dalla Chiara et al. 1999, p. vii.
2 Fermilab n.d.
3 LHCBE 2011.
4 LHCBE 2012.

In 2012, the Institute for Quantum Computing in Waterloo, Canada, teamed up with the Kitchener-Waterloo Symphony Orchestra to create "Quantum: Music at the Frontier of Science", which explored "the history of music and quantum science over the past century through music and narrative".[5] In 2015 (unbeknownst to us, who had begun preparing our project proposal in 2014), the Austrian scientists Putz and Svozil published an article in which they investigated various "ways of conceptualizing, rendering and perceiving quantum music, and quantum art in general".[6] They considered a quantisation of musical systems, a piano in particular, and explained how a diatonic, C-major scale could be quantised. They introduced "a nomenclature in analogy to classical musical representation [and] typical quantum mechanical features such as the coherent superposition of classically distinct tones, as well as entanglement and complementarity in music",[7] but without offering any actual artistic results. In the United Kingdom, a major centre for quantum music and other aspects of research combining music, science and technology was established at the University of Plymouth: the Interdisciplinary Centre for Computer Music Research (ICCMR), led by Eduardo R. Miranda. But unlike Miranda, who is both a classically trained composer and an expert scientist in artificial intelligence, the majority of researchers at the ICCMR are primarily computer scientists, mathematicians and AI specialists.[8]

Research proceeded in various directions, independent of our own work, after we started our first "Quantum Music" project in 2015. For example, in 2019 the American scientist Christopher L. Holloway and his team at the National Institute for Standards and Technology in Boulder (Colorado) experimented with making music with Rydberg atoms.[9] In 2021, researchers at the Quantum Engineering Technology Lab of the University of Bristol "collaborated with artist, producer and audio engineer Simon Small to investigate how quantum physics and technology can be used or utilised to generate sounds or music".[10] In the USA, a team led by Ryan Camacho at the Camacho Lab, established in 2017 at Brigham Young University, began creating music using quantum state number distributions.[11] Based on the frequencies calculated by Hans Cousto,[12] "the composer and sound artist Barnim A. Schultze aka Akasha Project developed a special composition-method for the octaveanalog [sic] transposition of the spectral measuring data (resonance-maxima) of the hydrogen atoms".[13]

While this overview is by no means exhaustive, it demonstrates the possible range of approaches for combining quantum physics and music and also shows that it has mostly been engineers, programmers and mathematicians who have been interested in quantum music, not professional musicians, composers and musicologists. This is probably because musicians tend to feel intimidated or out of their depth when confronted with physics or the natural sciences. The above research was thus focused mainly on quantum algorithms generating sounds (colours and/or pitches), rhythms or effects/modulations. With our projects, we took a different approach, taking *music* as our starting point. At the same time, thanks to a little help from our friends – quantum physicists – we felt bold enough to tackle the 'quantum' side of the project.

5 A short project description (from which the above citation is taken) and a full recording of the performance are available on YouTube, see Quantum 2012.
6 Putz/Svozil 2017, p. 1.
7 Ibid., p. 2.
8 ICCMR n.d.
9 Holloway et al. 2019.
10 QETL n.d.
11 CamachoLab n.d.
12 Cousto 2006.
13 Akasha 2010.

Finding a platform for artistic research

Our first pilot project, entitled "Quantum Music", emerged as a labour of love and friendship because the initial ideas were formulated by two pairs of friends. These were a tandem consisting of Vlatko Vedral, one of the most prominent quantum physicists today and a full professor at the University of Oxford, and his high-school friend Dragan Novković, a professor in the Department of Audio-Visual Technologies at the School of Electrical and Computer Engineering in Belgrade. Vedral and Novković devised a joint project combining their respective specialist areas, namely quantum physics, acoustics and music.

The second pair consists of the pianists Sonja Lončar and Andrija Pavlović (alias Andy Pavlov), an acclaimed, award-winning piano duo from Belgrade known as LP Duo. As avid fans and collectors of old analogue synthesizers, which they have consistently used in their live performances in different genres of music, Lončar and Pavlović have long dreamed of creating an ideal keyboard instrument that would combine the best features of classical pianos and analogue synthesizers. So they teamed up with Vedral and Novković, who possessed the expertise to turn their idea into reality.

At the invitation of LP Duo, I joined as the fifth member of this core group and as the project leader. My participation was needed, not least because I work at the institute attached to the Serbian Academy of Sciences and Arts and am therefore institutionally well positioned to submit a funding application for an art-and-science project. As an ardent admirer of the Darmstadt avant-garde of the 1950s and 1960s, especially Stockhausen,[14] I jumped at the opportunity offered by the "Quantum Music" project to create something new and to revive the spirit of the post-World War II avant-garde, in particular its 'obsession' with progress, innovation, technological breakthrough and, last but not least, new sound(s).

We found a suitable funding platform in the European Commission's programme Creative Europe, which was offering 60% financial support to small-scale cooperation projects including partners from at least two EU countries. We soon found two EU partners: from Denmark (the Danish National School for Performing Arts) and Slovenia (the Cultural Centre Kino Šiška), plus another partner from Serbia (the Centre for the Promotion of Science) and two associate partners (the University of Oxford and TodaysArt, a festival in The Hague). As the project progressed, other institutions joined as unofficial partners, including the Centre for Quantum Technologies at the National University of Singapore, Aarhus University and the Incontri Institute for New Music of the University for Music, Theatre and Media in Hannover.

When we decided to rely on Creative Europe funding, our project had to be tailored to this programme's objectives. These encompass European cooperation, audience development, transnational mobility and the need to create original yet accessible projects that can attract a wide, diverse audience. Creative Europe rarely supports projects aimed at a very narrow circle of experts and enthusiasts, opting instead for stronger visibility and impact; therefore, even 'innovative' projects must be sufficiently accessible and inclusive. This project-selection strategy is in tune with the general tendencies of the 2020s, including anti-elitism and decolonisation movements that have led to a loss of faith in 'elite' European modernist culture and even core European values or the idea of 'Europe' itself, which is nowadays regarded by some as "Eurocentric, Euro-supremacist, and Euro-universalist".[15] It is important to note that Creative Europe projects may not make a profit: all funding is spent on the project itself and, in addition to the 60% of the total budget provided by the EU, the partners in the consortium must raise an addi-

14 Among other things, I have written a book on his operatic cycle *LICHT,* see Medić 2019.
15 Weller 2021, p. 269.

tional 40% themselves. Projects funded by Creative Europe require idealism because the partners in the consortium are aware from the outset that there is no financial gain to be made from participating in the programme.

Choosing a direction

When deciding how to begin our explorations of the quantum phenomena and their analogies with music, we started with several ideas outlined by Vedral and Novković that we later assembled and published in the project catalogue entitled *Beyond Quantum Music 2019–2022:*

> At a physical level, music and sound in general can be viewed as waves of pressure, in which small packets of air compress and expand at a particular rate known as the frequency of the wave, that we perceive as a sound. Waves appear in many contexts in physics. Mathematically, wherever there is something that regularly repeats in time, it can be expressed as a wave. In quantum mechanics, these waves are far removed from our everyday experience. For example, quantum waves can correspond to the changing probabilities of finding a particle in a particular position. Fundamentally, however, the same mathematics that applies to waves breaking on the beach also applies to quantum physics. These mathematical similarities between sound and quantum mechanics form the basis of our attempt to create music from quantum mechanics. We can apply quantum mathematics, but rather than treating the output at any given time as a probability, we instead interpret the value as how compressed or expanded air should be at this time. The effect of this is that the probability waves from quantum mechanics are converted into audible sound waves.[16]

One of our first ideas was to probe quantum systems with some sort of input, with light lasers used to 'attack' the atoms. Another early idea was to try and simulate the 'sound' of quantum states. As explained in the catalogue, even without external 'probing',

> quantum systems change in time, typically at an ultra-fast rate. For example, an electron in the simplest Hydrogen atom naturally flickers between a quantum 'spin up' state to a 'spin down' state at approximately 1,420,000 times per second (if played as a sound, this would be far outside the range of human hearing, and so to hear these frequencies, we would have to slow them down considerably).[17]

Another idea was to explore one of the most specific quantum phenomena – coherent *superposition:*

> When a quantum system is in just one state […], the sound of the oscillation will sound like a pure tone at some frequency. A quantum system in a superposition of states at the same time will vibrate at multiple frequencies, thus the sound produced will be a chord. This system can be simulated on modern computers.[18]

Many parameters can be varied to change the rates at which the quantum system vibrates, and the project team's idea was that these parameters could be rigged for control by a piano keyboard so that pressing the keys could change the sound. Other ideas also involved the creation of musical pieces that would simulate or emulate certain quantum phenomena such as interference, entanglement and the Bose-Einstein Condensate (BEC) – the so-called 'fifth state of

16 Medić 2022a, p. 22.
17 Ibid., p. 23.
18 Ibid.

matter' that was predicted in 1924/25 by Albert Einstein and Satyendra Nath Bose, but experimentally achieved in quantum laboratories for the first time in 1995.[19] The BEC has provided scientists with the possibility of generating mechanical waves in quantum systems, thus leading to the establishment of a new scientific discipline of quantum acoustics.

During our experiments for the project "Quantum Music", we learned that sound waves created in the BEC are in the actual hearing range of humans. Our project thus started with a series of quantum-acoustics experiments during which particles exhibited characteristics that could be converted into audible sounds. As explained by Marko Rančić:

> At temperatures close to the absolute zero [-273.15 °C], matter behaved differently than expected […]. In the case of Bose-Einstein condensate, all wave functions of individual atoms collapse into one wave function due to low temperature and pressure (so-called Wave Function Overlap). One could easily make a joke: If one of the atoms of the BEC started dancing the folk round dance [*kolo*] known as 'Svrljiška Rumenka', the other atoms would immediately join the dance.[20]

This wave function overlap creates the quantum 'sound'; while one cannot hear it outright, our collaborator, the acclaimed Danish quantum physicist Klaus Mølmer, worked out equations and formulae to determine how such events occurred and thus managed to 'transfer' these inaudible quantum sounds into our world. The project team subsequently succeeded in synthesising sounds based on Mølmer's equations.

The next step was the creation of new hardware, the so-called 'hybrid piano' that transformed the classical piano into an analogue/digital instrument. During the first "Quantum Music" project (2015–2018), the team developed a version of it using magnetic sensors, which LP Duo used for its concert tour in 2017. As explained by LP Duo, the hybrid piano is "a combination of a traditional piano and digital synthesizer with analogue controls that allow different processing of acoustic and digital signals in real time."[21] This device instantly supplies concert pianos with new sound colours and hitherto unexplored expressive possibilities. The hybrid piano won third prize in the annual contest for the best technological innovation in Serbia in 2017.[22] The creation of the hardware was complemented both by the creation of a new software interface and also of sound banks that were developed using Klaus Mølmer's equations.[23]

In addition to this new instrument and its new sounds, LP Duo and their collaborating composer, Kim Helweg, wrote new pieces for two pianos and hybrid pianos inspired by the behaviour of quantum particles. Besides composing this new music, LP Duo also rearranged already existing music for their new, hybrid instruments (including works by the composers Ivan Božičević, Mark Mellits, Antonio Corea and others).[24] The show that LP Duo took on their 2017

19 The physicists who managed to create the BEC, Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman, were awarded the Nobel Prize in Physics in 2001 "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates", see Nobel Prize 2001.

20 "Na temperaturama bliskim apsolutnoj nuli materija se ponašala mimo očekivanja […]. U slučaju Boze-Ajnštajnovog kondenzata sve talasne funkcije pojedinačnih atoma urušavaju se u jednu talasnu funkciju zbog niske temperature i pritiska (tzv. Wave Function Overlap). U šali se slobodno može reći sledeće: Kada bi jedan od atoma BAK-a zaigrao kolo poznato kao Svrljiška Rumenka ostali atomi bi odmah zaigrali isto kao on." (Rančić 2011).

21 Lončar/Pavlović 2018, p. 114. In this article, Lončar and Pavlović provide details on the development and construction of this device, as well as its technical and interpretive possibilities.

22 A full recording of the TV show where the finalists presented their products and the jury reached its decision can be viewed on YouTube, see RTS 2017.

23 On the process of creating new sounds for this instrument, see Novković et al. 2018.

24 An extract from a recording of their live performance of the *Quantum Music* show at the Yugoslav Drama Theatre in September 2017 can be viewed on YouTube, see LP Duo 2018.

Fig. 1 The first of two prototypes of the hybrid piano (with magnetic sensors). Hardware created by the engineer Darko Lazović.

tour of six cities (Singapore, The Hague, Copenhagen, Aarhus, Ljubljana and Belgrade) also included an audio-visual narrative consisting of eight so-called 'chapters' aimed at explaining to the audience the most important phenomena of the quantum world. Each 'chapter' of the show was named after a certain quantum phenomenon: "Quantum Vacuum", "Collapse", "Double Slit Experiment", "Duality", "Bose-Einstein Condensate", "Bioquantum", "Entanglement" and "Teleportation".

However, Lončar and Pavlović were not entirely satisfied with the functionality of the first version of the hybrid piano because the magnetic sensors were sometimes unreliable, making live performances unpredictable and stressful for the performers. Their main challenge was to transform a classical analogue piano into a reliable digital instrument that would retain the dynamic and expressive range of a piano keyboard, its quality and sensitivity, the responsiveness to virtuosity in performance and the other technical advantages of a classical piano, but that could also be enriched with new colours and provide digital inputs and outputs. They accordingly decided to work on a new version in a second project, "Beyond Quantum Music" (2019–2022), creating an instrument that would use optic instead of magnetic sensors. Besides funding from Creative Europe, we raised additional monies from the Serbian Innovation Fund to help us develop a new prototype.[25] We thereupon assembled a team that could turn LP Duo's vision into reality, including engineers from the international company HTEC. The new instrument that was created was named DUALITY, and LP Duo went on to establish a company of that name that submitted an international patent, currently pending. This new version of the hybrid instrument proved to be much more reliable in live performance than the previous version and much easier to install.[26] LP Duo used it for its concert tour in 2022.[27]

25 SIF n.d.

26 The new version of the hybrid instrument allows both acoustic and digital signals to be processed in real-time. This device can be adapted to suit any grand or upright piano (it can be easily attached to any piano in less than 30 minutes) and is compatible with all standard types of computer and audio equipment.

27 A full recording of the show *Beyond Quantum Music* at the Yugoslav Drama Theatre in Belgrade of 3 October 2022 is available on YouTube, see LP Duo 2022.

Fig. 2 LP Duo (Sonja Lončar and Andrija Pavlović), *Quantum Music 2017* – "Teleportation" (Photo by Ivan Todorovski).

The science of "Quantum Music"

Although the "Quantum Music" and "Beyond Quantum Music" projects were conducted within the framework of the Creative Europe programme and their most visible (and audible) results were concert tours, new compositions, new instruments and new sounds, they also had a strong scientific component. The researchers working on the projects wanted to explore different possibilities for merging quantum physics with music, and after having made their breakthroughs they were eager to share their discoveries and to explain the purpose of their experiments and artistic decisions. This is why we organised two conferences on quantum music, both in Belgrade, in March 2018 and December 2022,[28] these being the final activities of the two respective projects. The first conference was followed by the publication of a themed issue on quantum music of the journal *Muzikologija/Musicology* in December 2018.[29] This contained nine articles, with contributions from researchers working on our project and also from external scholars who were involved in different approaches to quantum music and whom we had met through the conference. An initial group of articles in the issue surveyed various possibilities for a fruitful interaction between quantum physics and music, including the quantum superposition of two sounds, programming gate-based hardware and the phenomenon of interference that lies at the heart of quantum physics and is responsible both for many of the unusual aspects of quantum behaviour and for the aesthetic and philosophical implications of quantum music.[30] A second group of articles discussed the actual research conducted within the first "Quantum Music" project and its results, including the processes of synthesis and the analysis of sounds developed from both theoretical equations and the BEC experiments, the creation of the first prototype of the hybrid piano, and the conceptualisation of the piano duo "as an artistic embodiment of duality, entanglement and other quantum phenomena."[31] A third and

28 Medić 2022b.
29 Medić 2018.
30 Vedral 2018; Kirke 2018; Garner 2018; Marletto 2018.
31 Novković et al. 2018; Lončar/Pavlović 2018, p. 111.

final group of articles dealt with the collaboration between the Danish quantum physicist Klaus Mølmer and the composer Kim Helweg, the outcome of which was the composition *Superposition – Many Worlds* (2017) for two hybrid pianos.[32] Although the inspiration behind *Superposition – Many Worlds* was new, Helweg here employs relatively traditional compositional means. The title and subtitle of the piece

> refer to one of the characteristic phenomena of the quantum universe – the fact that particles can exist simultaneously in different states. […] However, as soon as a particle is located in the quantum space, the 'superposition' is lost and it 'collapses' into a single, defined state. […] Inspiration in quantum phenomena is also revealed by the titles of movements in Helweg's composition, because they correspond to the titles of the series of spectral lines of the hydrogen atom.[33]

Helweg's piece allows us to establish an analogy between the repetitive models of post-minimalist provenance and the 'waves of energy' in the quantum world. These 'waves' are the images of the 'superposition' of the particles, because they belong to all possible worlds until the moment when they 'collapse' into 'here and now'. In our analysis of Helweg's composition, Jelena Janković-Beguš and I established an analogy between Pierre Boulez's aims as expressed in his text "Technology and the Composer"[34] and the "Quantum Music" project, including close collaborations between scientists, engineers and musicians and the development and production of new instruments, paired with the composers' and performers' efforts aimed at learning and mastering the new technology.[35]

"Beyond Quantum Music"

The second project, "Beyond Quantum Music", was conceived to broaden and develop the productional, educational and artistic aspects of the pilot project – but aside from music, this creative research also encompassed visual and digital arts. The success of the first project and the enthusiastic response of audiences to our merger of art and science gave us confidence that this new consortium would successfully reach out to new audiences. When submitting our project application to Creative Europe in 2018, we chose 'transnational mobility' and 'audience development' as our objectives and priorities. The project started in October 2019, but only a few months later, the outbreak of the COVID-19 pandemic put immense obstacles before it. Our consortium was forced to adapt to the new circumstances, including organising an extension of six months to the project (it ended on 31 December 2022 instead of 30 June). We also made two changes to the members of the consortium and substituted certain events that had been planned with others. Since the quantum laboratories at the universities of Aarhus and Oxford (with whom we had previously collaborated) were closed to external researchers, all artistic and scientific research on the connections between quantum physics, music and arts was done at the Kavli Institute for Nanoscience at the Technical University Delft in the Netherlands. Although this collaboration had not originally been planned, Andrija Pavlović of LP Duo won a three-month artistic residency at the Kavli Institute in spring 2022. The Institute owns the

32 Mølmer 2018; Helweg 2018; Medić/Janković-Beguš 2018.

33 Ibid., p. 84f. The first six movements of Helweg's piece also bear the titles of the scientists who discovered the series of the hydrogen atom: *Prelude I, serie 1 "Lyman"; Prelude II, serie 2 – "Johann Balmers lustige Streiche"; Prelude III, serie 3 – "Paschen"; Prelude IV, serie 4 – "Brackett"; Prelude V, serie 5 – "Pfund"; Prelude VI, serie 6 – "Humphreys"; Prelude VII, serie 7; Prelude VIII, serie 8; Prelude IX, serie 9.*

34 Boulez 1977.

35 Medić/Janković-Beguš 2018, p. 90.

expensive, sophisticated equipment that is necessary for research of the complexity envisaged, as well as highly trained staff. Klaus Mølmer came from Denmark to Delft to conduct research with LP Duo, and that is where they completed the scientific part of the project and composed the music for their "Beyond Quantum Music" multimedia show. The most unexpected change to the consortium happened in the summer of 2022 when the preparations for their tour were already underway: our Dutch partner 'Stichting the Generator – TodaysArt' lost financial support from the city of The Hague and could not find alternative sources of funding. Since they could not fulfil their obligations, thereby putting the entire project in jeopardy, we had to replace them with another suitable partner. This was the MedILS Institute from Split, which helped us ensure the successful completion of the project.

Our objective of transnational mobility was achieved by organising many events throughout Europe, either live or prerecorded/streamed.[36] The tour "Beyond Quantum Music" in autumn 2022 consisted of several events, starting with an open-air concert in Novi Sad on 4 September 2022 that was part of the programme "Novi Sad 2022 – European Capital of Culture".[37] This was followed by a two-day event in Linz at the 2022 Ars Electronica Festival. The inclusion of our project in this, the largest, most important festival of its kind in Europe, gave it international visibility and prestige. The concert "Beyond Quantum Music" was performed on the main stage, in a large open-air pavilion, on 9 September 2022; LP Duo headlined the evening programme of the Festival and performed on the same stage as the legendary American avant-garde artist and musician Laurie Anderson, who was the main artist on the following day. This concert and the new hybrid instruments drew a lot of attention from the audience. On the next day, 10 September 2022, we gave a showcase presentation of the new hybrid piano at the Ars Electronica Centre, which was attended by many curious musicians and other artists.

The next stop of the tour was Split, with a two-day event organised by the MedILS Institute for Life Sciences. The tour concluded with a week-long event in Belgrade, Serbia, encompassing live performances, installations, and a presentation of the entire project and the new hybrid piano DUALITY. The concert "Beyond Quantum Music" at the Yugoslav Drama Theatre took place on 3 October 2022, followed by an exhibition and live performances on 10 and 11 October at the Centre for Cultural Decontamination, where selected artists from eight European countries presented their work: Timo Hoogland (The Netherlands), Joe Beedles (United Kingdom), Jiří Suchánek (Czech Republic), Tadej Droljc (Slovenia), Andreja Andrić (Denmark), Małgorzata Żurada (Poland), Marija Šumarac (Finland) and three artists from Serbia: Dragan Novković, Filip Mikić and Maja Bosnić. The international conference "Seven Years of Quantum Music – And Beyond" was held on 15/16 December 2022 in two formats: live (in Belgrade) and online, with participants from Denmark, the Netherlands, the United Kingdom and Serbia.

With regards to the objective of audience development, the pandemic caused a major shift in the cultural industry, forcing it to turn to the online presentation and distribution of events, including live streaming or broadcasting pre-recorded events, with listeners worldwide able to tune in. We made the most of this technological shift and ensured that all our events were dis-

36 The first event was a prerecorded concert "LP Duo presents: Beyond Quantum Music", given as part of the AI and Music S+T+ARTS Festival, a spin-off of the Sónar Festival in Barcelona, Spain, on 15 December 2021. Several events were organised in Delft as part of Andrija Pavlović's artistic residency: a welcome lecture and mini concert by Pavlović himself on 8 February 2022; a lecture by Klaus Mølmer on 24 February 2022; a lecture on quantum music by Sonja Lončar on 10 March 2022; and a final concert by LP Duo "Beyond Quantum Music" on 21 April 2022. All these lectures and concerts are now available online, see QuantumMusic 2022.

37 The city of Novi Sad was supposed to bear this title in 2021, but due to the COVID-19 pandemic, the majority of events were rescheduled for the second part of 2022.

tributed via such channels, streaming them live and/or uploading them to YouTube and other digital platforms.

The music on the "Beyond Quantum Music" tour consisted of new pieces composed and performed by LP Duo. While these works were inspired by quantum phenomena, with the sounds, visuals, dramaturgy and structure of the pieces worked out in collaboration with researchers from Delft, these pieces still suited the overall performance and compositional style of LP Duo, involving minimalism, postminimalism, the new simplicity and elements of popular music. In the comments printed in the catalogue, LP Duo explained their artistic research including their collaboration with the scientists Klaus Mølmer ("Intro", "Collapse"), Sander Otte ("Scanning Tunneling Microscope"), Kobus Kuipers ("Rogue Waves") and Eliška Greplová and Dimphna Meijer ("Qubit Funk").[38] For example, when working on "Qubit Funk", the quantum physicist Greplová and the bionanoscientist Meijer extracted the frequencies of qubit neuron experiments that LP Duo then transferred into sound. They created a powerful bass line and added a minimalist accompaniment that transitions into the funky groove of *qubit;*[39] this happens to the background of the sound of the quantum computers "Qu-tech" that LP Duo recorded in Delft.

Concluding remarks

Instead of a conclusion, I will here outline numerous questions that were prompted by the projects "Quantum Music" and "Beyond Quantum Music". Is it possible to write 'new music' today? If so, then what exactly is 'new' about this 'new music'? Can the present-day 'new music' be as relevant as it was some 60 or 70 years ago, given that the modernist ideology of constant progress has since been largely discredited, leading to the loss of funding to institutions, ensembles, radio stations, festivals and other links in the chain that supported this arguably elitist and non-commercial art form? Can quantum music initiate a new, impactful avant-garde wave? Does this music have to sound 'modernist' and 'avant-garde' in line with the aesthetics of the 'Neue Musik' of the 1950s and the 1960s to be considered 'new', even though that style itself is now over seventy years old? In other words, can music that sounds 'conservative', 'accessible' or even 'tonal' still be considered 'new', simply by being created in the 2020s?

I do not have definitive answers to any of these questions because they are dependent on whether one chooses to focus on conceptual, philosophical aspects or the compositional, technical 'newness' of quantum music (or any other kind of music). However, I hope that I have provided sufficient evidence that quantum music offers new paths for artistic research in the domain of art and science, fostering fruitful collaborations between mathematicians, physicists, bionanoscientists, acousticians, computer programmers, composers, performers and musicologists. Being still somewhat 'mysterious' and difficult to grasp for non-experts, quantum physics can nevertheless inspire artists, including musicians, to probe this uncharted territory and come up with new and exciting results, ranging from music 'composed' by quantum computers to new works written by actual composers curious about quantum phenomena.

The aforementioned questions have prompted me to try and determine what exactly was 'new' about the two projects that I led for seven years. I have come up with the following list:

38 Full descriptions of these pieces, together with the concert programmes and other information, are available in Medić 2022a, pp. 62–65.

39 *Qubit* is 0 and 1 at the same time, while *bit* is either 0 or 1.

- Exploring new and diverse possibilities for connecting music and science, specifically quantum mechanics and quantum sounds;
- Developing new hardware – the hybrid piano DUALITY;
- Establishing a new company, DUALITY, with the potential to create new jobs and revolutionise the piano-making industry;
- Developing a new software interface for the new hardware;
- Developing new sound banks consisting of sounds designed by following the equations and instructions provided by quantum physicists;
- New ways of illustrating and explaining complex quantum phenomena with music, thus making them better understandable to a wide audience of non-experts;
- Popularising and demystifying quantum physics through music;
- Contributing to humankind – helping to provide a deeper understanding of relations between the quantum world and our own.

The events that we organised through the two projects garnered lots of interest. All the concerts were sold out, and the exhibitions and presentations of the hybrid piano also attracted numerous curious attendees. Our further plans involve setting up a Quantum Music Festival and the mass production of the hybrid piano as soon as its patent is approved. Finally, since our projects were carried out under the auspices of the Creative Europe programme, we are also promoting European values that remain relevant, such as the right to culture and freedom of expression. Then there is the international, collaborative aspect of the project and its innovative research into creating new instruments, new sounds and new artworks, drawing from the broader pool of European talent including scientists, engineers and adventurous artists.

Although the works composed by Kim Helweg and LP Duo are stylistically not 'new' because they involve 'old' styles such as (post)minimalism and postmodernism, they employ new sounds based on quantum equations (although, seen objectively, similar sounds could have been synthesised even without quantum equations) and by being performed on new, visually and aurally attractive 'gizmos' – hybrid pianos, which transform classical pianos into powerful analogue-digital instruments. They also utilise, explain and illustrate quantum phenomena as described above and thus provide an exciting narrative and a strong educational component. As described in the introduction to this study, other researchers have taken different approaches by focusing on working with quantum computers and algorithms as a means of creating new musical works, or by focusing on the specifics of certain particles and their musical 'transpositions'. All of these approaches are equally valid; whether they will kickstart a new musical avant-garde movement is currently impossible to tell. Nevertheless, our exploration of the interaction between quantum physics and music has produced fascinating results and is encouraging further research into this field. Quantum music is likely to gain a greater following once quantum computers become more widespread and easier to use. We are still at the beginning of this technical revolution, and it is hard to predict how soon it will become mainstream. While science and technology can enable the discovery of new sound worlds, music can also contribute to science by inspiring experiments in the field of quantum mechanics, thus affirming the relevance of non-commercial art music in a profit-oriented, neoliberal world that is increasingly dominated by STEM disciplines, leaving little room for 'new music' on its own.

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