

Quantum Concept Music Score from Quantum Pictorialism: Musical Incarnation of a Bell-Pair under Measurements

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Abstract. We initiate the development of a new language and theory for quantum music, to which we refer as *Quantum Concept Music (QCM)*. This new music formalism is based on *Categorical Quantum Mechanics (CQM)*, and more specifically, its diagrammatic incarnation *Quantum Pictorialism (QPict)*, which is heavily based on *ZX-calculus*. In fact, it is naturally inherited from *CQM/QPict*. At its heart is the explicit notational representation of relations that exist within and between the key concepts of music composition, performance, and automation. *QCM* also enables one to directly translate quantum phenomena into music compositions in a both intuitively obvious, rigorous and mechanical manner.

Following this pattern, we propose a score for musicians interacting like a Bell-pair under measurement, and outline examples of how it could be live performed. While most of the Western classical music notation has heavily relied on linear representation of music - which does not always adequately capture the nature of music - our approach is distinct by highlighting the fundamental relational dimension of music. In addition, this quantum-based technique not only influences the music at the profound level of composition, but also has a direct impact on a live performance, and also provides a new template for automating music, e.g. in the context of AI-generation.

All together, we initiate the creation of new music formalism that is powerful and efficient in capturing the interactive nature of music, both in terms of internal and external interactions, and goes beyond the boundaries of Western classical music notation, which allows to use it in many different genres and directions.

1 Introduction

When passing from classical to quantum physics we change the language in which we describe nature. In first instance, mostly because of humanity's inertia, this language is as close as possible to things we are familiar with from classical physics. As such, Schrödinger introduced wave mechanics [1]. However, later, when John von Neu-

mann sought to gain some profound understanding of the new theory's implications, it became a formalism in its own right, namely the Hilbert space based quantum formalism [2].

Categorical Quantum Mechanics (CQM) [3, 4, 5, 6] or its diagrammatic incarnation in the form Quantum Pictorialism (QPict) [7, 8, 9] takes this a step further, by embracing from the very start that what has been identified by Schrödinger as “not one but the characteristic trait of quantum theory”, namely how systems compose [10]. This ‘relational’ focus also goes hand-in-hand with a view on nature in terms of ‘processes’ [11], that is, following Heraclitus rather than Parmenides. The new formalism makes it much more intuitively clear how quantum theory is different from classical theory, and what it enables, so the formalism is a direct witness of the new theory and its implications, and not just a vehicle for expressing it. This is not merely a convenience or ideology, as witnessed by the successes of CQM/QPict in a wide spectrum ranging from complex problems in quantum engineering [12, 13, 12] to quantum education [14]. Within the context of this paper the latter is particularly important: QPict has proven to have the potential to revolutionise quantum education by making quantum accessible at high school level and maybe even earlier [14].

Of course, traditional music notation also comes with implicit bias to what traditional Western music was supposed to be, for example, with the visual ‘distances’ between elements (e.g. noteheads, or even bars/measures) not matching the real proportions in music (e.g. temporal-durational distances, etc.). While suitable for the genres of Western classical music, it is not necessarily always adequate for thinking about music in a broad sense.

There are many more issues with it of course. For example, starting from the twentieth century, many distinguished composers have been experimenting with new forms and methods of music notation, because the ‘traditional’ music notation proved to be inadequate to repre-

sent new music. New ideas need new formalism, thus, several different directions and modifications of notation appeared. Some of the striking and experimental but efficient and lucid examples of modified music notation within the mainstream of Western avant-garde music include works by Stockhausen [15, 16], Cage [17, 18], Murail [19], Grisey [20], Lutoslawski [21], Maderna [22], Lachenmann [23, 24], Ferneyhough [25], and many others. Most of the modifications to the notation that were introduced by avant-garde music composers aimed at capturing the new sonoristic effects and extended methods of playing instruments. Some other modifications changed the approach to time in music. Nevertheless, in some cases each composer or composition school had its own system of notation, and thus overall when the new extended instrumental techniques emerged, it was not easy to find consistency in notation. Even now this largely depends on the individual preferences, and it became almost customary that composers preface their scores with legend/performance notes where every non-classical technique is being defined and described to facilitate the performance and (in certain cases) the perception of the score.

When passing to quantum music [26] it makes perfect sense to have a radical change in music language and theory, which we conceive of together under the umbrella of formalism, just as in the case of QPict. Retaining some of the traditional features, the formalism should be visual, but in a way that it tells the story about what the music is genuinely about, in particular its relational content, and not just something that happens to suit a piano keyboard, as a code for how to play it. The obvious way to do so, is for this passage to stay close to the one that resulted into QPict, given its fundamental relational and process-based foundation. Unlike other methods of notation, ours is not a mere modification or alteration, but a completely new, innovative and quantum-driven formalism, that also will make music notation more accessible. Given the importance of the notion of “composition” within music, this seems like a match made in heaven (or hell, like in Dante’s *La Commedia*). And this compositional structure should follow the important transition of this concept from “classical” to “quantum music”. which again can be enabled by QPict. Do note the deliberate ambiguous use of “composition” and “classical” here.

As an alternative formalism for quantum theory that brings relationships to the forefront, QPict is based on the following principle:

Whenever there are connections between entities in the described phenomenon, then these connections are also visible in the notation.

Translating this to music, our proposed formalism provides a vehicle that directly exhibits what actually is being thought of, composed or performed, as well as a direct bridge between musical composition and performance. All of this carries evidently over to music automation, and all of this while at the same time providing a direct bridge with the quantum world.



mutual conduction

Figure 1: Slide from a talk by Coecke at the School of the Art Institute of Chicago in the late 90’s, suggesting the use of quantum interaction as a new way for musicians to interact with each other.

Earlier related work. The first music generated by a quantum computer, meanwhile some 4 years ago, was achieved by a team under the pseudonym Ludovico Quanthoven [27]. As the title of the paper states, the approach was based on Quantum Natural Language Processing (QNLP) [28, 29], which in turns, is based on CQM/QPic [30, 31, 32]. More specifically, the pictorial linguistic structure of of QNLP were replaced by musical structure, and the linguistic meanings were replaced by musical meanings. The QNLP software package *lambeq* [33] could then easily be turned into a quantum music software package *Quanthoven*. So from its very start quantum music has been enabled by CQM/QPic.

The suggestion for bringing the interactive nature of music to the forefront using quantum goes back to talks in by one of the authors in the late 90’s as seen in Figure 1. The relational nature of music is also clearly visible in the structural diagrammatic analysis of the score of Abdyssagin’s *Symphony No. 2 “Chaos and Order”* (2023) in Figure 2.

Examples of how quantum phenomena are reflected in music at the level of composition and numerous other correlations can be found in Abdyssagin’s book [36].

2 Colourless ‘classical’ notation

The notation introduced below augments a variety of existing music notations, including traditional staff-notation, guitar tablature, (cf. Figure 3), as well as other modern forms of music notations. In fact, it is not even restricted to music notation, and could likely also apply to notations for dance, animated art etc. Here for the sake of simplicity we will introduce everything in traditional staff-notation.

In this paper we assume familiarity with basic quantum theory, and basic ZX-calculus [37]. For our notation, we will borrow the spiders of QPict [8, 9]. The default semantics of spiders is “being the same” for everything that is connected by it, like an equal sign with more (or less) than two arguments, or a generalised Dirac delta [8]. Connecting spiders means transfer of sameness, as indicated in Figure 4.

For now, we mainly focus on the relationships between different instruments, say qubit 1 and qubit 2. Notes, as spider dots, being connected by a wire expresses that

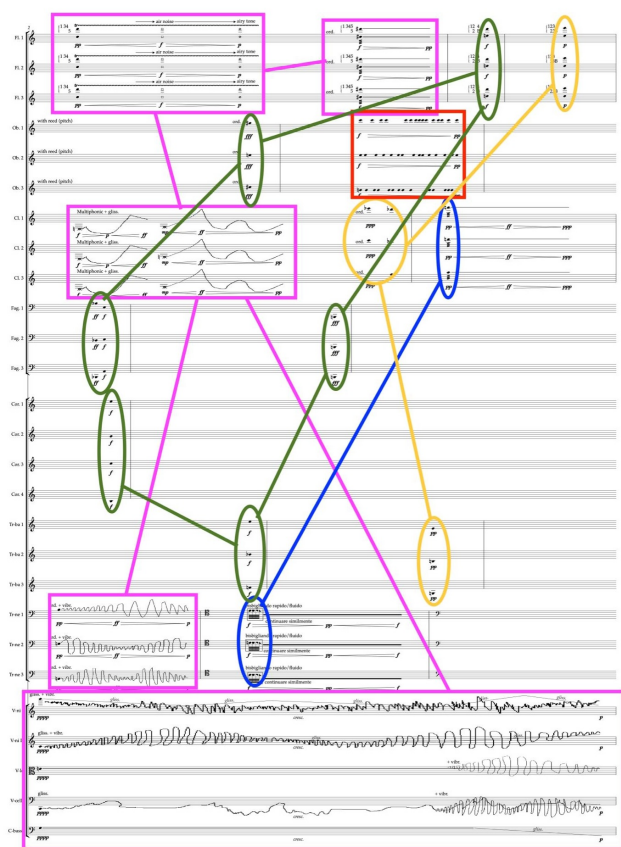


Figure 2: The score of Abdyssagin's Symphony No. 2 "Chaos and Order" (2023), indicating the relational nature of music, in a way that instantiates part of the formalism introduced in this paper [34, 35].

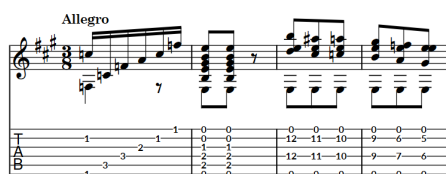


Figure 3: Traditional music notation and corresponding guitar tablature, which specifies where to play particular notes – there may be up to 6 different ways to do so, affecting playability and sound texture.

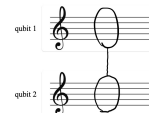


Figure 4: The spiders of QPic and their compositions as an expression of "sameness", as indicated in red.

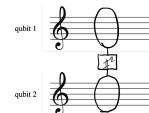
these notes are the same. Hence, at this point the notation doesn't add any content.



A bigger 'blob' around the staff means that whatever is in the blob is the same. This can either be specified, or a variable, e.g. for improvisation, or it can be a high-level abstract structure that can be further refined.

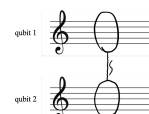


So a plain spider gate means doing the same, as in an identical relation between what is in the circles. A gate on the wire allows one to express alternative relations between what is in the circles, of which there could be many variations, for example, a $\sharp^n$ symbol may indicate that 'part' of either qubit should be performed half-tone higher.



There may be other relations that are defined in terms of a "meta-glossary", for example indicating what one means by "opposite/dual", etc. The gate can also be left as a variable, which in a live performance could be incarnated by a third party. The gate can also be taken to be a genuine quantum gate, that indicates relationships such as complementarity, by means of a Hadamard gate.

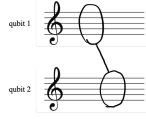
Thus far we took "sameness" to be identical, but just like in mathematics (cf. same vs equivalence vs isomorphic), there can be many notions of sameness, for example, "alike", "inspired by", "anticipates", "follows" etc. Specifying this could be part of the meta-glossary. Possibly, if different forms of sameness are required in one score, this could also be indicated, e.g. using " $\sim$ " notation.



One may also want to consider partial notions of sameness, e.g. sameness only at level of notes, or sounds, or rhythm, which could be indicated by extra notation in the gate. Alternatively, this could again be subsumed in the meta-glossary. A meta-glossary will serve the function similar to the role of performance notes/legend in contemporary music scores where many extended instrumental techniques need to be described and elucidated.

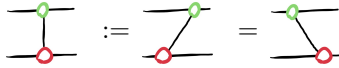
3 Lead and follower

In improvised live performance, sameness would typically imply that one musician takes the lead and the other one follows. And this, of course, can change during the performance. This can be indicated by a tilted gate.



Alternative indications could be an arrow. The above however reflects the cause-consequence relation in a way that is more aligned with physics by providing a temporal connotation. In computer music, this tilting will in general not be needed.

Remark 3.1. In ZX-notation, in principle, all gates are always tilted given that each wire is assigned to either be an input or an output. However, since the two possible tilts turn out to be equal by the axioms of the calculus [8, Lemma 9.46], one denotes it as non-tilted in order to stipulated that equality.



4 Colourful ‘quantum’ notation

Now we introduce the notion of quantum measurement into music notation, for the purpose of composition and/or performance. This means that we will have to distinguish between ‘thick’ or ‘doubled’ quantum wires and blobs, vs ‘thin’ or ‘single’ classical wires and blobs [8, 38].

In QPict, measurements constitute the passage from thick quantum wires to thin classical wires, and doing the opposite represents encoding of classical data as quantum data [8, 38]. For all that we said above, the wires of staff and gates could all have been the same, either quantum or classical, so we ignored the issue. Below we will explain how measurements and quantum gates can be used together in a score without any ambiguity, which is necessary for example when one wants to entangle the qubits before measuring.

For the purpose of composition and/or performance, a measurement means the following, which here we take to be on one of two qubits, that may be entangled:

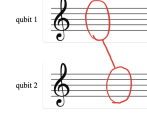
- A choice of a measurement is made for one of the qubits, which includes specification of what the two eigenstates of the measurement are, for example, a Z -measurement with eigenstates $|0\rangle$ and $|1\rangle$. This is done by whatever/whomever plays the role of the observer.
- They then decide when to perform the measurement, say on qubit 1.
- When the measurement is initiated, the state of qubit 1 collapses to the eigenstate corresponding to the measurement outcome. This is a non-deterministic process, but for which some mechanism may be provided.
- Depending on the relationship between qubit 1 and qubit 2, the latter collapses to a corresponding state. In the case that the relation is “being the same”, this is the same state as qubit 1 collapses too.

We can depict the measurement as follows:

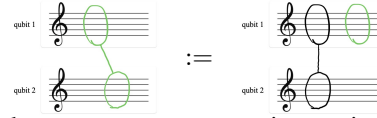


(2)

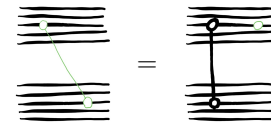
where the colour represents the choice of measurement. A different measurement, say an X -measurement relative to a Z -measurement, could then be depicted as follows:



The wire connecting the blobs indicates the influence of qubit 1 on qubit 2. Strictly speaking, this implicitly assumes that the two qubits are entangled:



However, the more compact notation as in (2) may be more appropriate for musical performance, indicating direct causal connections at the time they should be accounted for. Translated to the QPict formalism, the above equation becomes, when for simplicity instantiating to a specific note as measurement outcome:

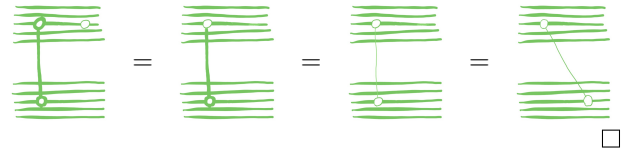


(3)

So this is where the thick vs thin wires and blobs becomes crucial. We now formally prove our claim.

Lemma 4.1. Equation (3) indeed holds.

Proof. First note that we are allowed to colour the “the same” gate green, as the identity is basis-independent, as well as the staff lines, as they represent the space itself, so we can instantiate them in any basis. Using ‘bastard spider fusion’ [8, Section 8.3.3] we obtain:



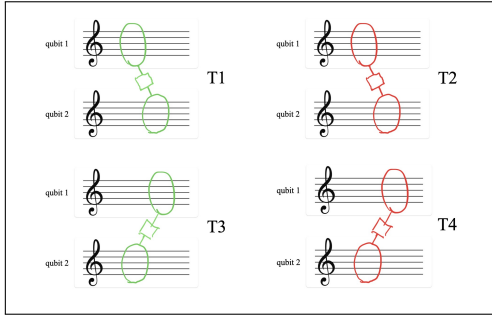
□

Having absorbed prior entanglement in the measurement notation, we can now also vary that entanglement beyond “the same”, to any kind of entanglement:



5 “Bell” score

We restrict ourselves to two qubits under measurement, given some prior entanglement that for simplicity we take to be fixed for the whole score. The measurement specifics, including who/what decides when and which measurement takes place is to be specified in the meta-glossary. This is the composition “Bell”, made up from some movements that can be specified in the meta-glossary:



Note that we put a fixed gate, which is unavoidable when the two qubits are realised in a different manner, and hence need a means of identifying states and measurements. We illustrate this on an example in the next section.

6 “Bell” example arrangement

The arrangement described here has already been performed. The core idea of this quantum-musical experiment was to demonstrate the applicability of Quantum Concept Music to music performance. From a musical perspective, seen as a musical experiment, it adopts the following principles: (1) Performance in music can be conducted using an analogue of quantum measurement. (2) The audience can act as both the observer and instigator of empirical changes. (3) Musicians can interact as an entangled pair under measurement. (4) Live improvisation is a suitable setting for realising the above.

Concretely, the arrangement for the “Bell” score involves the ‘performance’ of two qubits – say qubit 1 and qubit 2 – on two different instruments, that will be forced to interact in a very particular way.

6.1 Qubit 1: Quantum Guitar

One example of a qubit is realised by means of the Quantum Guitar introduced in [39]. The realisation of the qubit is very direct here, as quantisation of a guitar constitutes associating a qubit to any of its playable states, using Moth’s Actias synth of Figure 5 – heavily inspired by the earlier Q1Synth [40].

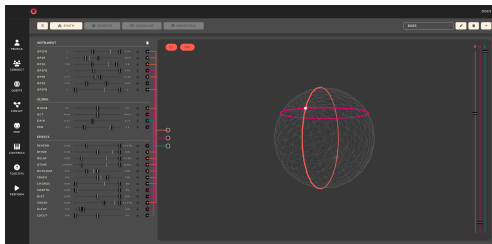


Figure 5: The qubit within Actias.

6.2 Qubit 2: Grand Piano

Here, a logical-musical qubit, together with two complementary measurements on it, is mentally created. Projecting the Bloch-sphere on a plane in the usual way, we will describe two orthogonal lines in the plane, each spanned by a pair of eigenstates, which then also define the two complementary measurements:

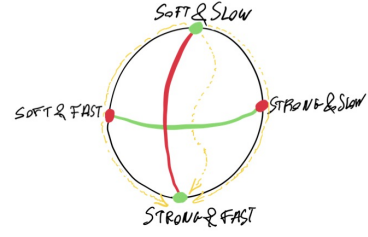


Figure 6: Mentally created qubit for a Grand Piano. There are many paths for going from (Soft and Slow) to (Strong and Fast) as indicated in yellow.

- Soft (Delicate) vs Strong (Loud)
- Slow vs Fast

These two sets of opposite states are ‘generic’ in the sense their ambiguity and ‘wideness’ of interpretations allows the performers to precisely catch each other’s improvisation. This is of a crucial importance for an unprepared improvisation.

These pairs obey a (weak form of) quantum complementarity in the sense that being strict in one observable tells nothing about the other one. An alternative stronger notion of complementarity arises by considering the following alternative pairs of eigenstates:

- (Soft and Slow) vs (Strong and Fast)
- (Soft and Fast) vs (Strong and Slow)

As states these are now all four mutually exclusive. Moreover, respecting Bloch-sphere geometry, there is now no unique path between the two eigenstates, for example, one can go from (Soft and Slow) to (Strong and Fast) equally well passing either via (Soft and Fast) or via (Strong and Slow). Moreover, just like on the Bloch-sphere, there are paths to go through neither. Qubit 2 is depicted in Figure 6. Strictly speaking, here we are only filling half of the sphere, which corresponds, in ZX-calculus terms, for the observables only allowing phases to take values in $[0, \pi]$.

6.3 Entanglement

The entanglement constitutes a mapping from qubit 1 to qubit 2. The colour choice in Figure 6 indicates a canonical one in terms of identifying corresponding Z- and X-eigenstates. For example, if qubit 1 is measured against (Soft and Slow) vs (Strong and Fast), and the outcome is (Strong and Fast), then the state of qubit two should move Actias in the $|1\rangle$ -position. If the outcome is (Soft and Slow), then the state of qubit two should move Actias in the $|0\rangle$ -position. The same goes for (Soft and Fast) vs (Strong and Slow) relative to Actias positions $|+\rangle$ and $|-\rangle$, and vice versa, when qubit 2 is measured.

6.4 Measurement choice and non-determinism

These can be chosen/determined by the musicians themselves, or a third party, including the audience.

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