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Q-MUSE: A QUANTUM COMPUTER MUSIC SYSTEM DESIGNED FOR A PERFORMANCE FOR ORCHESTRA, ELECTRONICS AND LIVE INTERNET-CONNECTED PHOTONIC QUANTUM COMPUTER

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Abstract: **Quantum computing is a form of unconventional computation utilizing quantum effects as a fundamental part of its calculations. It has already been used in practical signal encryption in the 2010 Soccer World Cup, and there is competition amongst many governments to build more powerful and practical quantum computers. Although quantum computing is the most widespread and invested in form of unconventional computation, there have been no implementations of artistic systems with live hardware quantum computers. Furthermore there is a vast gap between public understanding of classical digital computing and of quantum computing. Q-Muse is a quantum computer music system design for a specific performance. The Entangled Orchestra is a performance for Orchestra, Electronics and Live Internet-Connected Photonic Quantum Computer. There are many types of quantum computation hardware implementations including Nuclear Magnetic Resonance, Trapped Ions, and Optical Computing. Q-Muse incorporates the third of these – a system that utilizes wave guides, phase-shifters and beam splitters to compute with entangled photons. The processor is located at University of Bristol in the UK is accessed over the cloud. It can implement a Controlled NOT gate (CNOT) – an essential component in the construction of quantum processors. The CNOT gate is part of a two gate set that can be used to build any type of quantum computing process. The resulting musical performance will provide not only a representation for the quantum processes in the chip, but a proof-of-concept for using hardware quantum computing processors in the computer-aided arts.**

1. INTRODUCTION

In this paper a practical set-up is described for performing live using a quantum computer [1]. Like classical computing, quantum computing works with bits – i.e. values of 0 and 1. In quantum computing these are called qubits and in this paper we will examine qubits represented by light waves. Quantum light waves act like particles as well as waves [2] – these particles are called photons. Most people are familiar with the light interference patterns seen during experiments at high school. This is normally explained as light wave peaks interfering with light wave troughs. However many experiments have also been done to show individual photons of the light build up interference patterns. The wave patterns seen in interference in fact summarize the *probability* of finding an individual photon at a particular point. The axioms of quantum mechanics say that one may only calculate the probability of particle being in a certain state. In fact before a particle is measured, it can be thought of as being in multiple possible states. It is this superposition of states and its implications that leads to the useful features of quantum computing. A qubit is actually a superposition of multiple bit-states – a property which leads of the speed ups found in theoretical quantum computing. This speed-up effect has been shown to allow much faster factorization of numbers – threatening cryptographic security [3].

Like traditional classical computers, quantum computers are based on logic gates. A standard gate is the Controlled NOT (C-NOT gate). It is two inputs a Control and Target input. A classical C-NOT gate acts like a NOT gate on the Target, as long as the Control is 1. If the control is 0, the C-NOT acts as an Identity gate, allowing the Target to pass through unchanged.

The hardware quantum computer described in this paper [4] implements a quantum version of this gate, based around photons. Photons are obtained by focusing a 404nm laser on to a piece of nonlinear crystal (Bisumuth Borate). This causes the crystal to probabilistically spit out 808nm photon pairs, in a process known as Type I spontaneous parametric down conversion. The chip, which performs several experiments that would each ordinarily be carried out on an optical bench the size of a large dining table, is 70 mm by 3 mm. It consists of a network of tiny channels which guide, manipulate and interact single photons. Waveguides are made with a higher refractive index than their surroundings, so that photons can propagate along them by total internal reflection. The waveguides in the integrated optical device are made from silica and sit in a wafer of silicon, which allows things to be kept on a relatively small scale – the chip is 70mm x 3mm.

Using eight reconfigurable electrodes embedded in the circuit, photon pairs can be manipulated. A schematic is shown in Figure 1 at the end of the paper. The circles with numbers in them are known as phase shifters – and will be discussed later. They are able to change the phase of the photons (remember that photons behave like waves, as well as like particles). The points where the lines meet are called beam splitters, which will be explained later and also enable further quantum effects to be added to the calculation.

The key elements are the inputs marked 1 to 4 in Fig. 1. In this C-NOT the inputs are each represented by two photons. These allow the inputs of the quantum C-NOT to be specified, as shown in Table 1.

Table 1: Setting up inputs on the quantum C-NOT

Control	Target	Inputs to send photon in to
0	0	1, 3
0	1	1, 4
1	0	2, 3
1	1	2, 4

Using the quantum effects created by the beam splitters and the phase shifters, the chip is used in this paper as part of computer music system for live performance called Q-Muse. The chip hardware – shown in Figure 2 – is located at the University of Bristol and can be accessed with only a few seconds lag over the internet.

A JSON web API is provided which gives full access to the Quantum Computer. It can use any modern programming language (Mathematica, Python, Javascript, MATLAB ...) to talk to our servers through this API and get data from the computer. Below is an example API call, getting counts from the chip with all phases set to zero (i.e. the circles with floating point numbers in Figure 1 all set to 0). This is the Mathematica code to make the call:

```
counts=Import["http://cnotmz.appspot.com/experiment?
phases=0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0&accessToken=
XXXXXXXXXXXXXXX", "JSON"];
```

An access token is provided to users by the Bristol laboratory for accessing the device. The above call will return something like:

```
{"counts": {"2,3": 0, "1,3": 80, "1,4": 0, "2,4": 28}, "max": 80, "sum":
108}
```

which gives the number of photons detected across the output groups at the far right of Figure 1. It can be seen how these relate to qubit values using Table 2. In this example outputs 1 and 3 had an 80 photon count.

2. RELATED WORK

Previous designs for performances with quantum mechanical processes have either been metaphorical, or based on simulations, online or offline simulations. The most impressive has been Danceroom Spectroscopy [5] in which quantum molecular models generate live visuals. Dancers are tracked by camera and their movements treated as the movement of active particles in the real-time molecular model. Thus the dancers act as a mathematically accurate force field on the particles, and these results are seen in large scale animations around the dancers.

The performance which is closer to the current work is Cloud Chamber [6]. In this, physical cosmic rays are made visible in real-time, and some of them are tracked by visual recognition and turned in to sound. A violin plays along with this, and in some versions of the performance, the violin triggered a continuous electric voltage that change the visible particle tracks, and thus the sounds.

The piece Background Count is a pre-recorded electroacoustic piece that incorporates historical Geiger counter data into its creation [7].

In terms of offline simulations, the most closely related to this paper is the web page Listen to the Quantum Computer Music [8]. Two pieces of music are playable online through MIDI simulations. Each is a sonification of a well-known quantum computation algorithm. One is Shor’s Algorithm [3] – this was the factoring algorithm mentioned earlier. The other is a database search algorithm known as Grover’s algorithm [9]. The offline sonification of quantum mechanics equations have also been investigated in [10], [11] and [12], with the third being an attempt to create a musical signature for the Higgs Boson at CERN before its discovery.

In terms of orchestral pieces, there have been no live interactions with quantum behaviours, though the orchestral piece “Music of the Quantum” [13] was written as an outreach tool for a physics research group, and has been performed multiple times. The melody is carried between violin and accordion. The aim of this was as a metaphor for the wave particle duality of quantum mechanics, using two contrasting instruments.

The performance system described in this paper differs from the above by being live, non-simulated, and significantly non-metaphorical. It consists of two movements – one which uses Q-Muse as a live computer music instrument playing along with the orchestra, and one which uses Q-Muse to demonstrate and exhibit a key issue of quantum computation – entanglement. Before describing these, it is necessary to discuss the work that led to the formulation of the current ideas behind entanglement: known as Bell’s Theorem.

3. BELL’S INEQUALITY AND ENTANGLEMENT

The mathematical formulation of quantum mechanics – as supported by a multitude of experimental results for decades – has implications which cannot be explained in the way that we are used to explaining the physics we learned in high school and every day experience. One such implication which most people are unaware of is the question of what makes two particles separate from each other. For example what makes two light particles (photons) different objects? Consider the common sense notion of the separateness of say two wooden planks A and B 100 metres apart. If you move plank A, plank B does not move. If you break plank B, plank A does not break. In fact most local actions and observations on planks A and B are independent of each other. Conversely, if you push the end of a plank, and another plank 100 metres away moves, you would assume they are connected – perhaps by a piece of string or a rod. They in effect become one object – the “plank plus string plus plank” object. This is our common sense notion of things being separate independent objects, or one connected object.

At the subatomic level it is not so simple. In fact it is possible to use a process to generate two photons which are as separated as it is possible for two particles to be. They could be a million light years apart, not influencing each other by force fields. Yet it can be shown by the mathematics of quantum mechanics that doing something to photon A effects photon B. Because there is no known force field or interaction between the photons during this process, then by our common sense notion of separate objects, the photons are not entirely separate objects. But they are, clearly. They are a million light years apart with no interaction. This process of being separated particles but in some sense not separated was intolerable to Einstein; and the fact that the mathematics of quantum mechanics enabled this to happen, proved to him quantum mechanics was wrong. A methodology was found to quantify these issues as a testable inequality called Bells Inequality [14]. Amazingly, when experiments were done in the 1960s, it was found that this inequality could be violated, thus implying that the entanglement predicted by the mathematics happened in the real world, leading to an avalanche of philosophical debate, which still continues.

We do not wish to concern ourselves with this debate here, but wish to create a musical mapping from a quantum computer live whose results show the effects of entanglement. The quantum computer used here can generate entangled photons using beam splitters. Although the entangled photons are only separated by a tiny distance, from a physics point of view they are entirely “different planks”. They have no detectable physical interaction. Yet statistically they behave as if they are connected, are part of one larger object. It is these statistics that are amplified through the computer music system.

Before explaining the mapping and control system, it is necessary to explicate an experiment that exhibits the effects of entanglement. Here is an analogical explanation of that experiment - the Prisoners’ Postman:

Two soldiers Alice and Bob are caught and placed in separate huts either side of a compound, outside of hearing range of each other. Their jailor Eve is a kindly person but likes playing games. She tells each soldier that if they can give her some wrapping paper and something to put in it each morning, then she will send it as a present to one of their families. There are gaps under the prison huts and each day there is always a 50/50 chance of Alice and Bob both finding either a stone or some old newspaper within a hands grasp. So once Alice and Bob have chanced across one or the other, Eve will ask each for the address of one of the families. Alice can give her own address or Bob’s, and Bob can give his own address or Alice’s (they know each other’s because they are old comrades-in-arms). But neither can know what the other has said. As long as they don’t both find only pebbles, and they both choose the same address, Jailor Eve will use one of the pieces of newspaper as wrapping and send the other item (be it pebble or scrunched-up newspaper) to that address. This as a sign to their family they’re alive and okay. If they choose different addresses, Eve will not send the package, except…Jailor Eve is as bored of *hanging around the compound as Alice and Bob, so she invents a twist to make the daily game more interesting. Even if Alice and Bob provide different addresses, there is one case where Eve will still send a package. This is if Alice and Bob both fail to provide wrapping paper, i.e. they find only pebbles. In that case Eve will find some newspaper and wrap both pebbles for them and send the package randomly to one of the families. So to summarize: Alice and Bob get to send out a letter between them either if they both pick the same address and at least one of them finds wrapping paper, OR if they pick different addresses and they both only find pebbles. The question is: assuming that each has a 50/50 chance each day of finding a pebble or newspaper within reach, what strategy should Alice and Bob following in choosing addresses to increase the chance that at least one letter is sent? Oh and they do get a chance every so often to set a strategy, because extra prisoners come in in transit, so Alice and Bob are placed in the same hut for that one day, and then returned to isolation from each other.*

If Alice and Bob pick a random strategy, i.e. they randomly select an address whether they find paper or pebble, on average they will send out 1 letter every two days – i.e. a 50% a day probability of success. If, after being in a hut together, they agree to select only Alice's address for 7 days, and then only Bob's address for 7 days, this will increase to a 75% a day probability of a parcel being sent. In fact both agreeing to select the same address at the same time is the optimal strategy, Over the years, if Alice and Bob try different strategies, they will still hit the upper maximum of 75%, because they cannot communicate before choosing the addresses. They are on different sides of the compound. It can be proved that without communication, the limit is 75% for any strategy because Alice's knowledge is local to her, and Bob's is local to him.

To understand the entanglement experiment, consider two photons generated by a beam splitter so they are entangled. After the photons have separated – Alice performs an operation on the photon based on her chosen address and whether she's found a rock or a paper. Bob does a similar thing on his photon. So the state of the two photons now fully describes whether Alice and Bob can win. But neither photon can communicate or affect the other. When the photons are observed at the detectors, you would expect them to be in win state 75% of the time. However – they are in a win state 85.36% of the time (to be precise it can be shown to be $0.25*[2+2^{0.5}]$). There is a ten point increase. If the entanglement is removed, the probability goes down to 75%. In this case the photons are on a single quantum computer chip, but the experiment has been performed with photons on separate islands, and this increase has still been observed. The mathematics implies what Einstein called "spooky action at a distance" faster than the fastest possible speed in the universe (the speed of light).

4. Q-MUSE

The Q-Muse system is a quantum computer music system consisting of a number of computer music patches (like those found in MAX/MSP), gestures controllers, quantum state control buttons, and audio and signal outputs. The full schematic is shown in Figure 3 at the end of this paper. Different parts of the Q-Muse system are used for the two movements of The Entangled Orchestra. Hence Q-Muse is best described by describing each of the two movements of the composition.

4.1. Movement 2 – A Phase You're Going Through

This is fully pre-scored for orchestra and electronics. The Q-Muse system is used to create a new instrument, played by live the first author. Gesture and button controllers are attached to the performer's arms, and the button presses and movement gestures are transmitted wirelessly to Patch Q_3 which converts them into parameters for the quantum computer. In particular for the angles of the phase changers. The resulting photon detections are sent over the internet to patch Q_4 and converted to sound. Moving the phase changers has the effect of changing the quantum superposition states of the photons, and thus the statistics of the photon detection rates at different outputs.

This movement is thus a mini-concerto for orchestra and quantum musical instrument. So as long as the performer does not move his arms, the photons are constant phase. Then as one arm moves significantly, one phase changer rotates, then the other and the other rotates. Other controls will change various timbre, loudness and frequency elements of the generated sounds. These are implemented as a series of sub-patches within patch Q_3 and selected using buttons on the gesture controller system.

In classical physics the idea that a photon can be a particle and have a phase is contradictory. In quantum mechanics it is possible to think of a photon as exhibiting both wave and particle properties simultaneously. Waves can have a phase angle, indicating the location of a wave's cycle at a particular time. Changing the phase of the photons in the chip causes them to interfere destructively or constructively with each other. To understand this, consider a subset of the sort of paths contained in the chip, as shown in Figure 5. The far left shows the inputs for the qubit – putting in a photon into (0) gives a cubit of value 0, an input in (1) gives a qubit of value 1. In the centre is a beam splitter which splits the light "wave", and at the far right are the photon detectors which count the number of photons arriving in each path.

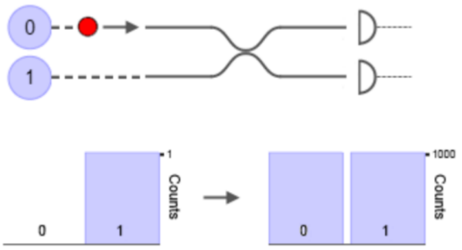

Figure 5: A simplified photon path and the result

If a single photon is put in through (0) or (1) 2000 times, then we would expect to detect the photon half the time at the top detector and half the time at the bottom detector. Between the beam splitter and the detectors, the photon is in what is known as a superposition state, it is "blurred" across paths 0 and 1. Adding another beam splitter gives Figure 6. If a photon is sent into (0) then as a result of the extra beam splitter is will always be detected at the lower detector for the following reason. At the first beam splitter it blurs across both paths, and at the second beam splitter these blurred paths interfere with each other behaving like light waves. This interference causes the probability of the particle being detected at the top detector to become zero. Thus the particle is always detected at the bottom detector.

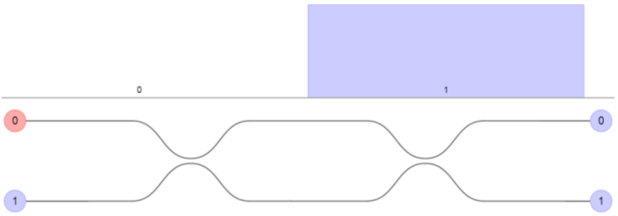

Figure 6: Photon system with an additional beam splitter.

(Technically this interference is happening to the spatial wave function; however describing this precisely is beyond the scope of this paper.) This interference effect can thus be manipulated using the phase shifters in the wave guides. Figures 7 and 8 show what happens when a phase shifter is added. Figure 7 applies a phase shift of 0.5π radians to the "part" of the blurred photon in that wave guide. This causes interference effects at the second wave guide leading to photon detection happening at top and bottom detectors with equal probability.

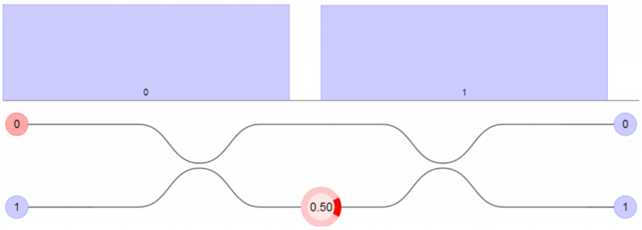

Figure 7: Photon system with an additional beam splitter.

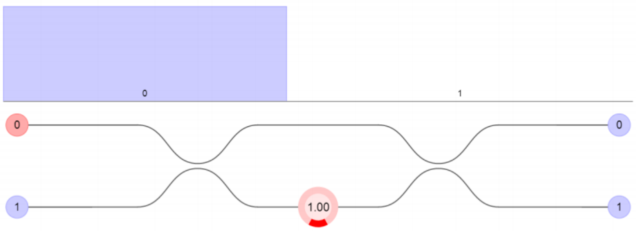

Figure 8: Photon system with an additional beam splitter.

The phase shifter in Figure 8 is set to π radians. This creates an interference effect in the second beam splitter that leads to the waves cancelling out for the bottom detector. So the photon will always be detected at 0. Applying different phrase shifts causes different probabilities of detecting the photon at different detectors. The demonstration of these interferences is a mathematical task which – although not highly advanced – would require stating the axioms of quantum mechanics and doing some lengthy mathematical expansions – thus they will not be shown in this paper.

However looking at Figure 1, and the brief description of the JSON Web API earlier, it can be seen that the phases can be set in various paths dynamically and photon counts returned, over the internet. Thus it becomes clear how Figures 7 and 8 provide a method for creating sound based on the photon "interference patterns" created in the abstract quantum space.

The phases can be changed via arm gestures, and detectors can be added and removed from the patch using button presses on the gesture detecting devices. The patch can then generate sound based on which detectors are active and what the arrival rate of photons. For example, suppose the gestures are at a certain angle and height. This leads to Patch Q_3 making a call to the QC of the form:

counts=Import["http://cnotmz.appspot.com/experiment?phases=[P1],[P2],[P3],[P4],[P5],[P6],[P7],[P8]*&accessToken=XXXXXXXXXXXXXXX", "JSON"];*

where [P1], [P2], etc are phase values in radians mapped from the gesture angles and heights of the performer. The value returned to Patch Q_4 will be of the form:

{"counts": {"2,3": [X1], *"1,3":* [X2], *"1,4":* [X3], *"2,4":* [X4]*}, "max":* [M1234], *"sum":* [S1234]*}*

where X*i* is the number of photons detected across various detectors. These integers are mapped on to musical features via Patch Q_4 in Fig. 3. These sub patches include:

SP1. X1, X2, X3, X4 are mapped to four pitch quantized sine wave generators G*i*, whose pitches are proportional to the X*i*.
SP2. They are mapped to a single sound generator whose frequency is proportional to X1, loudness proportional to X2, loudness attack envelope proportional to X3, and loudness release envelope proportional to X4.
SP3. The detection rate is sonified by having four sound generators, each of which gives out short sounds. The frequency of the sounds is different for different detectors. The rate of the sound production for each is proportional to the photon count for its associated detector.
For example consider the returned values:

{"counts": {"2,3": 0, "1,3": 80, "1,4": 0, "2,4": 28}, "max": 80, "sum": 108}

The results would be, based on the implicit scalings (whose full description is beyond the space available in this paper):

SP1. Chord: C2, C6, C2, F3 [range is C2 to C6]
SP2. Pitch C2, Max MIDI loudness 102, Attack rate 8 seconds, Release rate 1.1 seconds [rate ranges are 8 seconds to 0.01 seconds]
SP3. Generator rates in sounds per second (S/s): 0, 13, 0, 5 [rate range is 0 to 16]

The key element of this movement is that the resulting computer music soundscape is being adjusted by a quantum process. The changing of phases of "spread out photon probability waves" has no classical equivalent. Thus this will be the first truly live quantum computer music – as it directly manipulates quantum effects before musifying the results.

4.2. Movement 1 – The Entangled Orchestra

An equivalent experiment to the Prisoner's Postman can be run on the chip, with the non-entangled version give a 75% win and the entangled giving an approximately 85.36% win. The issue is how to make that increase audible in a meaningful way. To utilize this in a music performance a method called statistical amplification is used. The amplification is provided by a non-linear function:

$$y = \begin{cases} 1/(k-x); & x < k \\ z; & x >= k \end{cases} \qquad (1)$$

where $k = 0.25*[2+2^{0.5}]$ – approximately 85.36% - and x is the rate at which the "letters" are sent per day. It can be seen that as the rate x gets to k, the amplified value y gets larger exponentially. z is called the Asymptotic Replacement Constant. If the rate ever does hit k, it will become infinite which is obviously undesirable. For the classical rates below 75%, the amplified value stays below 10. At the 50% pure chance rate it the amplification stays below 3. Above 75% it grows rapidly. 80% is amplified to 19, 82% to 30. 84% to 74, and 85% to 281.

The orchestral configuration that uses this function is as follows. The orchestra is divided into two halves A and B, with two conductors. Each part has its own mini-sections – e.g. violins, violas, brass etc. The quantum computer / orchestra connection system is shown in the left side of Fig. 3. Photon detections containing information about a "win or lose" of the Postman game are sent over the internet. These are converted to statistically amplified win/lose statistics by Patch Q_2. This sends a signal via the amplification function to a silent metronome Conductor A can see. The signal is low pass filtered to avoid uncontrolled jumps in the metronome.

When Conductor A presses the Entanglement button shown to the right of Fig. 3, it triggers entangled states between photons in the quantum computer. Thus before pressing the button the metronome will on average represent the non-entangled probabilities. After pressing the button the probability of a win will rise and this rise will be amplified mathematically.

In between the two orchestras sit two movement performers with their backs to one another. They represent Alice and Bob and are playing the Prisoner's Postman in front of the audience. In between them is another movement artist playing the prison camp warder Eve. The warder indicates whether Alice and Bob have won or lost by posting a letter in a post box prop. Alice and Bob each sit at small tables on which are the Measurement Basis Button Sets shown to the left of Fig. 3. The buttons control the quantum computer over the internet, allowing them to set up states and get the results. However they cannot control whether the states are entangled or not, only conductor A can do that.

Initially the entanglement is switched off. The musical score is in segments and the movement between segments is signalled by Conductor A. Initially orchestra A and orchestra B look to conductor A. Every time the statistically amplified "win" rate goes above 20 it is indicated to conductor A, who signals to both orchestras to move to the next segment. Each segment consists of dialogues between two or more instruments across the two sub-orchestras. Gradually as the segments go on, they become more dense and sustained, and result in both orchestras playing continuously. Orchestra B at a higher tempo, and orchestra A at a much lower one. In fact A is at a tempo of X/130 – where X is the statistically amplified win rate (as low as 10 for the non-entangled version). So initially orchestra A will only be changing notes every 6-12 bars. At this point orchestra A will continue being controlled by conductor A, but orchestra B will be taken over by conductor B.

After a time indicated by the musical score, the entanglement is switched on by conductor A. This will cause the win rate to rise from a maximum of 75% to a maximum to up to 85.36%. Because of the rate at which Alice and Bob play the game, and the low pass filtering, it will take a few minutes for orchestra A's tempo to increase, but then it will catch up with orchestra B. At this point, conductor A takes control of both orchestra's again. The tempo maximum will be about 3-6 notes a second. At which point entanglement is considered to be fully demonstrated musically and the movement is ended with a crescendo.

In the background of this, there will be projection showing elements of the chip hardware live via webcam, together with visualisations of the photon detections.

5. CONCLUSIONS

We have introduced the system Q-Muse, a computer music system that incorporates a ground-breaking photonic quantum computer in the cloud based at the University of Bristol. Q-Muse is focused on two forms of performance. The first is driven by statistics that demonstrate the effects of entanglement a signalling system for musicians. The second implements an instrument based on quantum effects that can be manipulated by gestures in real-time. It is aimed to premiere for The Entangled Orchestra in November 2015.

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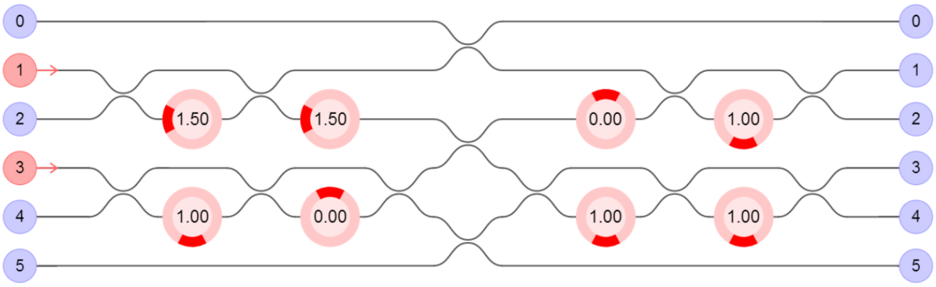

Figure 1: Schematic of the Photon Quantum Computer showing photons being input on (1) and (3) and various phase changer settings in the pathways.

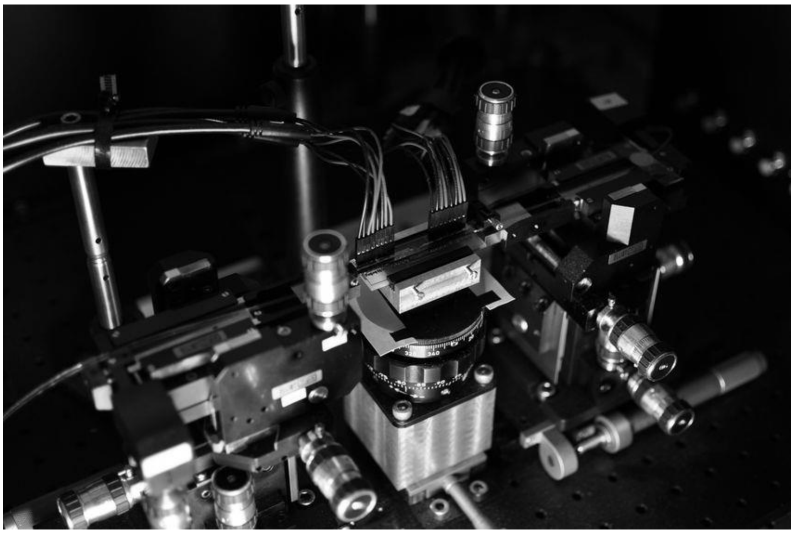

Figure 2: Actual Physical Chip, casing and connectors connected to the internet

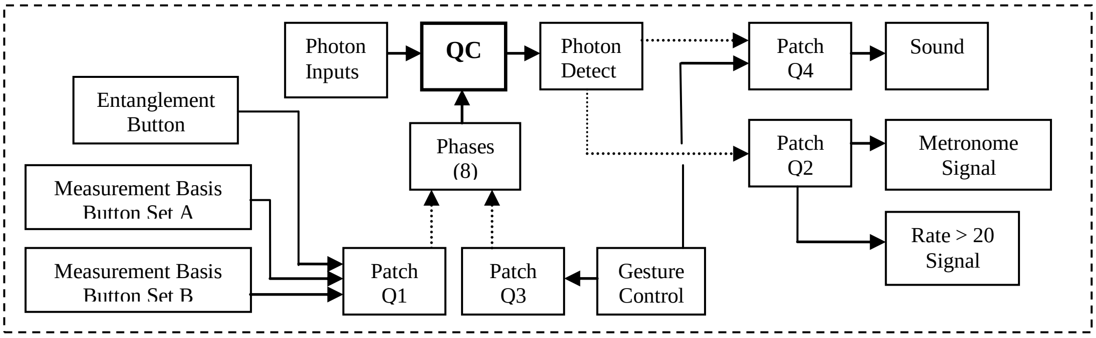

Figure 3: Schematic for the full Q-Muse system, dotted lines indicating an internet connection