# Background Information

Over thousands of years, we as a species have compiled a vast amount of information with the hope of gaining a better understanding of the inner workings of our universe - the laws of nature. Technology is produced by deliberately using our knowledge of these laws in order to get nature to do something that is useful for us. We can build boats, not just because we know that some objects float on water, but because we can use the knowledge we have gained about *why* an object floats to our advantage, and create vastly complex structures based on this. Building a quantum computer would, essentially, be the same, but instead of using Archimedes principle, we are deliberately trying to take advantage of what nature allows on the microscopic scale (which, as it turns out, is very different to what we see in day to day life). Also, we're not certain that a quantum computer would make a very good dinghy. What we *do* know, is that quantum technologies could make a wide array of very appealing, but currently impossible, tasks possible. Things like guaranteed secure communication through always being able to detect the presence of an eavesdropper, ultra high precision measurements to push sensors to the limit of what nature allows, and simulation of molecules to significantly reduce the amount of time it takes to find new medicines and drugs. While we haven't quite got to that point yet, we are making good progress. As an example of this, we present a quantum photonic chip which is able to perform some of the fundamental operations required for a large scale device, and invite you to play around with it for yourself.

As the desire to understand will always be essential to the development of technology, here's a brief and basic overview of some of the key concepts related to our chip. There are some links to further resources for those who are keen to find out more (and perhaps, for a few from the next generation of quantum information scientists).

## Photons and Waveguides

The light that enables us to see the world around us is made up of microscopic particles – **photons**. Photons are **elementary** particles, meaning that they can't be split up in to anything smaller. They are one of the fundamental building blocks of the universe. Don't let the word "particle" fool you though, photons can also be refracted and interfere with each other (and themselves) – things only possible for waves. The reality is that photons (and all other **quantum particles**) exhibit what is known as **wave-particle duality**, meaning that they do things that "only" waves do as well as things that "only" particles do. We obtain our photons by focusing a 404nm laser on to a piece of nonlinear crystal (Bisumuth Borate $BiB_4O_6$). This causes the crystal to probabilistically spit out 808nm photon pairs, in a process known as type I spontaneous parametric down conversion. We can then collect these photons, and manipulate them in order to perform useful tasks.

An optical **waveguide** is, as the name suggests, a structure which guides photons from one point in space to another. 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 our integrated optical device are made from **silica** and sit in a wafer of **silicon**, which allows us to keep things on a relatively small scale – compare our 70mm x 3mm chip to a bulk optics realisation of the same circuit, which might be on the order of 1m x 1m.

Papers and links:

- Wiki page on photons
- Wiki page on optical waveguides

## Qubits

We use photons in waveguide pairs as **qubits**. Just like a bit is a **unit** of **binary** information in the computers of today (we call these computers "classical" computers, and a bit a unit of "classical" information), a qubit is a unit of binary **quantum information**. The main difference between the two is that whereas a bit has to be either a 0 or a 1, a qubit can also exist as a **superposition** of 0 and 1, meaning that can it partly as a 0 and partly as a 1 at the same time. In fact, there are infinitely many combinations of a singe 0 and a single 1 that a qubit can exist as. As you can imagine, this gives qubits the advantage of having a sort of inherent parallelism in terms of computation - more than one question can be explored by the computer at one time. Not only that, but people envisage a quantum computer that *itself* exists as a superposition of different processes, taking the possible parallelism even further.

The fact that photons are largely free of noise and decoherence (something that is a real issue for some other ways of realising qubits) makes them good candidates for qubits. They can also be easily manipulated in order to perform single qubit **gate operations**, the basis for many computational processes. That they travel, by definition, at the speed of light, and can be made compatible with the standard telecommunications optical fibres for long distance transport is something of a bonus.

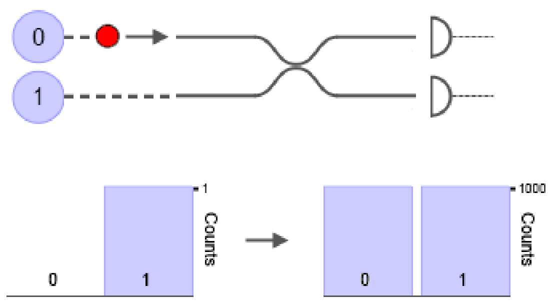
Papers and links:

- Wiki page on qubits

# Single Photon Experiments

## Beam Splitter / Directional Coupler

A beam splitter is a device which lets a certain fraction of light pass through it, while the rest of the light is reflected from the surface. Usually, people talk about "50/50" beam splitters, which let half of the incident light pass through while reflecting the other half. All of the beam splitters on our chip are "50/50" beam splitters, apart from the three down the middle, which let 2/3 of the light pass through them. You might be wondering: if a photon can't be split in to smaller pieces, what happens when a single photon is sent in to a beam splitter? Let's see:

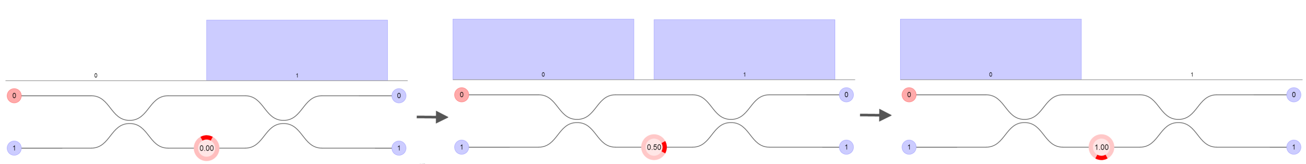



Each time, we detect a photon in one of the paths after the beam splitter. If we repeat this enough times, we see that half of the time the photon is detected in 0, and the other half of the time it is detected in 1. But how does the photon decide which way to go at the beam splitter? Does it flip a coin? Well, quantum mechanics tells us that reality is far stranger than that – the photon doesn't decide! It smears in to a kind of blur of taking one path and the other *at the same time* - we say that the photon is in a **superposition** of being in paths 0 and 1. Perhaps weirder still, it's not until the photon reaches the detectors that it makes its decision, and that's why we only detect it as being in one place. This all seems a little far-fetched, and like it could be explained without talking about any "blurring". How do we know that this is what really happens? For this, we need to add another photon (see Quantum Interference)

Papers and links:

- Wiki page on beamsplitters

## Mach Zehnder Interferometer (MZI)



A Mach-Zehnder Interferometer is made up of two beam splitters, with a device that can apply some sort of a rotation to a photon, in one path, in the middle. We call these rotation applying devices "Phase Shifters". Phase shifters are what allow us to have control over the results that we expect to see at the detectors, and as such allow us to use the chip for many different experiments. Say we send a photon in to an MZI in path 0, with the phase shifter set to a value of 1 (π radians). This causes the photon to appear at the out of the other end of the MZI in path 0 with 100% certainty. Similarly, if we set the phase shifter to a value of 0, the photon definitely appears at the end in path 1. Setting other values on the phase shifter make it so that there is a probability that the photon will end up in either path, but these probabilities depend on the value of phase shifter. In a way, we have a beam splitter for which we can fine tune how much light passes through, and how much gets reflected. But why does this happen? From before, we know that the photon becomes "blurred" over the both paths by the first beam splitter. At the second beam splitter, the two smeared out parts **interfere** with each other (like waves), constructively and/or destructively. The amount of constructive/destructive interference depends on the amount of rotating that the phase shifter does.

Papers and links:

- Wiki page on Mach-Zehnder Interferometers

# Multi-Photon Experiments

## Quantum Interference

Now let's move on to an experiment with two photons. Up until now, the actual results that we have seen can be explained without the need for any quantum physics, so how do we know that we need it to describe the way that nature works? We need to find an experiment which gives results which are inconsistent with what you would expect if you were not treating a photon as a quantum particle. We go back to our 50/50 beam splitter, but now, instead of just sending a photon through in path 0, we also send a photon through in path 1 at the same time. Let's label these photons a & b respectively. Intuitively, there are four possibilities:

1. Both photon a and photon b stay in the same path.
2. Both photon a and photon b switch paths.
3. Photon a stays in the same path and photon b switches path.
4. Photon a switches path and photon b stays in the same path.

Because we have a 50/50 beam splitter, and because there is nothing special about either path or photon, it is tempting to assume that all situations are equally likely (each happens ¼ of the time), and so ½ of the time we get a single click at each detector (from adding the probabilities for situations 1 and 2). This is, in fact, what would happen if a photon wasn't a quantum particle, and it does *not* predict what we see experimentally. What we see is that we *always* get two clicks at one of the detectors. How does quantum mechanics let us predict this outcome? It does not deal with probabilities (which must always be positive) but with **probability amplitudes**, which are complex valued and therefore can combine to give negative numbers. So, according to quantum mechanics, situations 1 and 2 actually cancel perfectly, leaving only the possibility of one of the detectors clicking twice – exactly what we see experimentally.

For a short exercise in investigating the difference between classical and quantum interference, see the document on how to operate the chip simulator.

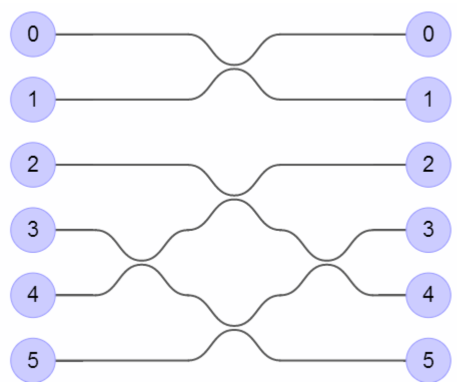
Papers and links:

- Quantum interference section of the Wiki page on interference
- Hong, C. K.; Ou, Z. Y. & Mandel, L. (1987). "Measurement of subpicosecond time intervals between two photons by interference". Phys. Rev. Lett. 59 (18): 2044–2046.

## Controlled NOT (CNOT) Gate

If we look carefully at the chip, it is mostly split in to a top half and a bottom half with no link between the two, apart from at the centre of the chip – we allow some interaction between the top half and bottom half via the CNOT gate. Interacting two quantum particles can give rise to a phenomenon called entanglement, and what Einstein described as "spooky action at a distance". Entanglement between two photons can lead to correlated results which can be described by quantum mechanics, but not with classical "local hidden variable" theories, and provides the basis for many of the potential benefits that quantum computers will have over the machines of today e.g quantum teleportation, QKD, Shor's algorithm. The CNOT gate gives us access to these distinctly quantum methods of processing and communication.

Unlike a beamsplitter or MZI, the CNOT gate is designed for use with 2 qubits. It is part of a **universal gate set**, along with the Hadamard gate (which is the mathematical operation carried out by the beam splitter) and the arbitrary phase




gate (realised by our phase shifters), meaning that any (unitary) operation can be carried out by arranging combinations of these three gates (technically, as the phase gate is tunable to apply any arbitrary phase, it represents an infinite number of gates). The classical counterpart to the quantum CNOT gate would be a reversible XOR logic gate, and as such, its operation is as follows: conditional on qubit A (the **control** qubit) being 1, apply a NOT operation on qubit B (the **target** qubit), and do nothing otherwise. This is handily summarised by a truth table:

| **Before** | | **After** | |
|---|---|---|---|
| **Control** | **Target** | **Control** | **Target** |
| 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 |
| 1 | 1 | 1 | 0 |

Note that in order for our CNOT circuit to act like a mathematical CNOT operation, we must define and restrict a few things. Firstly, we must only have 2 photons injected at a time, and we label modes 1 and 2 the control qubit logical 0 and 1, and modes 3 and 4 as the target qubit logical 0 and 1. You might notice that photons can end up being in modes 0 or 5, or that in some cases after the CNOT there are two photons in a control/target mode. For computations, we simply discard these outcomes - a process calling **postselecting**. The probability that we get photons in the right paths for computation after the CNOT is 1/9, meaning that we have to multiply all output probabilities by a factor of 9 in order for all of our postselected probabilities to add to 1.

Papers and links:

- Wiki page on the CNOT gate
- O'Brien, JL; Pryde, GJ; White, AG; Ralph, TC; Branning, D (2003). "Demonstration of an all-optical quantum controlled-NOT gate". Nature 426 (6964): 264–267

# Additional Information (for researchers)

## CNOT Unitary

Our entangling gate does not perform a canonical CNOT operation. Given appropriate choice of modes for control/target qubits, postselection and renormalisation of outputs, the unitary is given as:

$$\hat{U}_{CNOT'} = \begin{pmatrix} 0 & -i & 0 & 0 \\ -i & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \tag{1}$$

Or, in other words:

$$\hat{U}_{CNOT'} = \begin{cases} i\sigma_x \text{ performed on target qubit} & \text{control qubit is in state } |0\rangle \\ \sigma_z \text{ performed on target qubit} & \text{control qubit is in state } |1\rangle \end{cases} \quad (2)$$

Where $\sigma_x$ and $\sigma_z$ are the Pauli $x$ and $z$ operators respectively.

## Chip Unitary

The 2 qubit unitary for the chip, given the same conditions as for the CNOT, is given as:

$$\hat{U}_{CHIP} = \left[\hat{U}_f(\xi_5, \xi_6) \otimes \hat{U}_f(\xi_7, \xi_8)\right] \cdot \hat{U}_{CNOT'} \cdot \left[\hat{U}_i(\xi_1, \xi_2) \otimes \hat{U}_i(\xi_3, \xi_4)\right] \quad (3)$$

where

$$\hat{U}_i(\xi_a, \xi_b) = e^{\frac{-i\sigma_z \xi_b}{2}} e^{\frac{-i\sigma_y \xi_a}{2}} \quad (4)$$

$$\hat{U}_f(\xi_a, \xi_b) = e^{\frac{-i\sigma_y \xi_b}{2}} e^{\frac{-i\sigma_z \xi_a}{2}} \quad (5)$$

and

$$\begin{aligned} \xi_1 &= \phi_1 - \pi & \xi_2 &= \phi_2 \\ \xi_3 &= \phi_3 - \pi & \xi_4 &= \phi_4 \\ \xi_5 &= \phi_5 + \pi & \xi_6 &= \phi_6 - \pi \\ \xi_7 &= \phi_7 + \pi & \xi_8 &= \phi_8 - \pi \end{aligned} \quad (6)$$

where $\phi_i$ is the phase introduced by the $i$th phase shifter. Arbitrary 2 qubit state generation is possible when restricting the input to the state $|00\rangle$

Please see Shadbolt, P. J. et al. Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circuit. Nature Photon. 6, 45–49 (2012) for more information on the chip.