Interaction-free measurements on IBM quantum computers

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Outline

Quantum Simulation on Quantum Computers

Quantum Simulation on Quantum Computers

1. Quantum computers have the capability to do things that a classical supercomputer cannot.
2. A programmable quantum computers can simulate very complex quantum systems.

> ‘Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.’
>
> — Richard Feynman (1982)

3. Many such systems have been realized, such as ultracold quantum gases, polar molecules, trapped ions, etc.
4. We want to explore the realization of a simulated photonic system on a superconducting quantum computer using famous quantum experiments.
5. Experiments about interaction-free measurement and quantum nonlocality are curious cases that demonstrate the peculiarity of the quantum world, and could serve our purpose.

Elitzur-Vaidman Bomb Tester

Elitzur-Vaidman Bomb

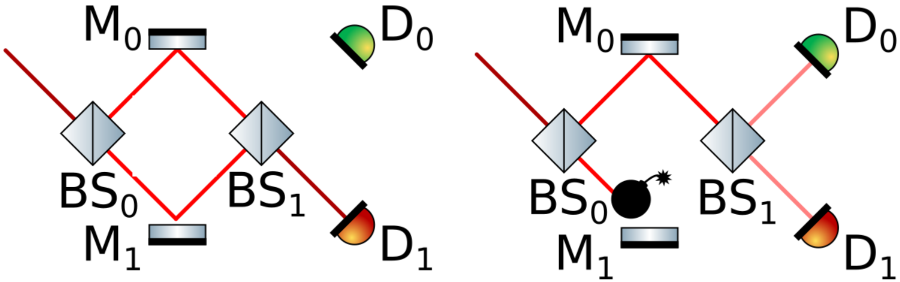

Figure 1: Elitzur-Vaidman bomb illustration.

1. An optical experiment that demonstrates interaction-free measurement.
2. With a half-silvered mirror as the beam splitter, there is a 25% chance the bomb will be detected.
3. In the basic case, there is still a 50% chance the bomb will explode, and a 25% chance of non-detection.

The Kwiat's paper (1994)

Interaction-Free Measurement

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in the presence of the object, it is the indivisibility of the quantum which enforces the mutual exclusivity of the possible outcomes.

For a lossless system, the fraction η of measurements that can be interaction free is given by

$$\eta = \frac{P(\text{det})}{P(\text{det}) + P(\text{abs})}, \tag{1}$$

where $P(\text{det})$ is the probability of detecting the presence of the object, and $P(\text{abs})$ is the probability that the photon is absorbed by the object. In the case considered above, $\eta = RT/(RT + R) = (1 - R)/(2 - R)$, which tends to the upper limit of 50%. We stress that from the viewpoint of a single event, a successful measurement is *completely* interaction-free (in the sense that the photon is not absorbed by a perfectly absorbing object), even though the likelihood of such a measurement is only 1/2.

Here we present a different method that in principle allows the fraction of interaction-free measurements to be arbitrarily close to unity. Consider the arrangement in Fig. 1. A single photon is incident from the lower left port of a series of connected Mach-Zehnder interferometers. The reflectivity of each of the N beam splitters is probability $P = \cos^2(\pi/2N)$ that it continues to travel on the lower path instead. The *nonfiring* of each detector projects the state onto the lower half, and the whole process repeats [5]. Clearly, the probability that the photon is now found in the lower exit after all N stages is just the probability for it to have been reflected at each beam splitter:

$$P = \left[\cos^2\left(\frac{\pi}{2N}\right)\right]^N, \tag{2}$$

which in the limit of large N becomes $P = 1 - \pi^2/4N + O(N^{-2})$. Of course, the probability that one of the detectors *is* triggered is just the complement of (2), so that for a lossless system $\eta = P$ (Fig. 2). Already for $N \geq 4$ there is a greater than 50% probability of making an interaction-free measurement, thereby surpassing the limit of the original EV configurations. As the number of stages becomes very large, the efficiency of the scheme approaches 100%. From the perspective that each of the interrogations modifies the evolution of the wave function, thereby inhibiting the transference, our scheme may be considered an application of a discrete form of the quantum Zeno effect [4,6].

Quantum circuit approach

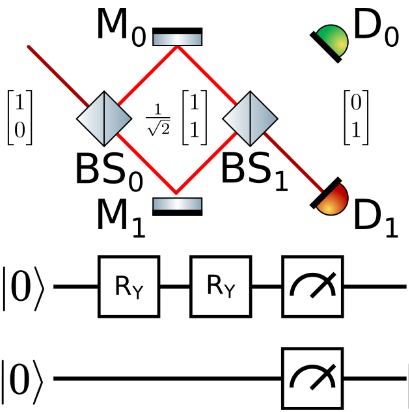

Figure 2: Without active bomb.

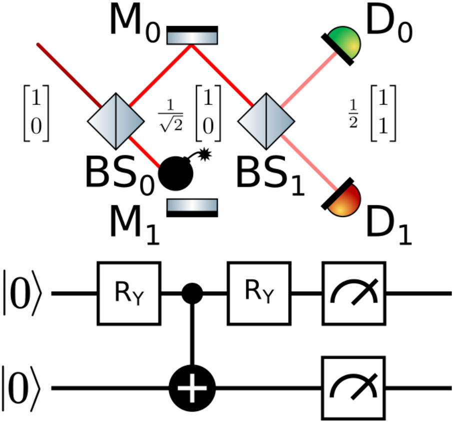

Figure 3: With active bomb.

1. $|0\rangle \rightarrow R_y(\pi/2)|0\rangle \rightarrow \frac{|0\rangle+|1\rangle}{\sqrt{2}}$; $\quad R_y(\pi/2)\frac{|0\rangle+|1\rangle}{\sqrt{2}} \rightarrow |1\rangle$.
2. $|00\rangle \rightarrow CNOT|00\rangle \rightarrow |00\rangle$; $\quad |10\rangle \rightarrow CNOT|10\rangle \rightarrow |11\rangle$.

Running on IBMQ

1. The IBM Quantum Cloud has a number of different quantum computers accessible to the public: Yorktown, Burlington, Essex, London, Ourense, Vigo, Valencia, Santiago, Athens (5 qubits), Melbourne (15 qubits).
2. They have different calibrations, coupling maps, and accuracy sensitive to different circuits/algorithms/tests.
3. We ran the aforementioned circuit on the IBMQ Athens:

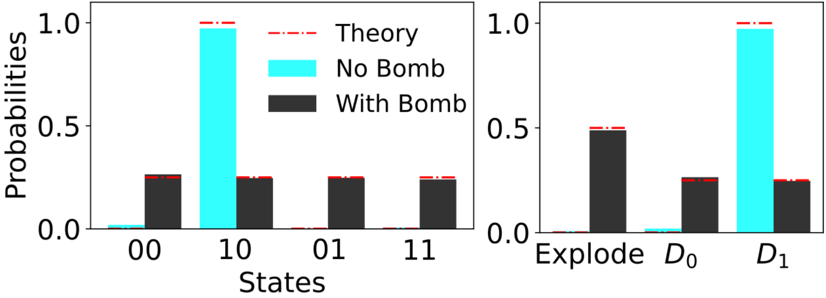

Figure 4: On IBMQ Athens.

Running on different devices

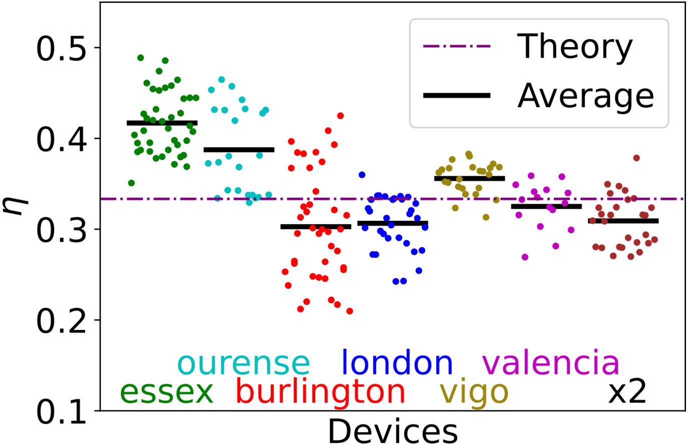

Figure 5: Running on different devices.

1. Undetected bomb can be push through the apparatus again, boosting detection rate to 0.33.
2. Later devices have less scattered results.

Running the improved circuit

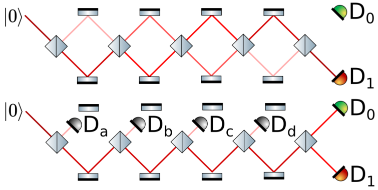

Figure 6: Optical experiment.

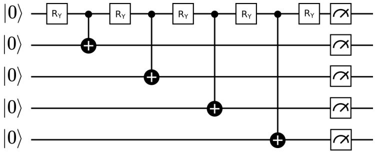

Figure 7: Quantum circuit.

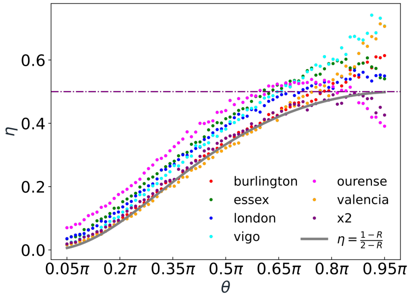

Figure 8: Changing the angle.

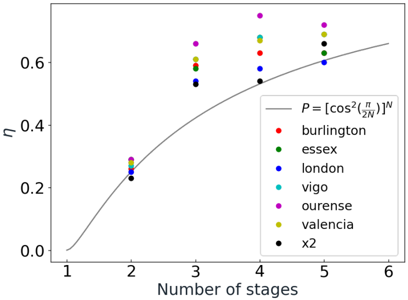

Figure 9: Adding stages.

Running the improved circuit

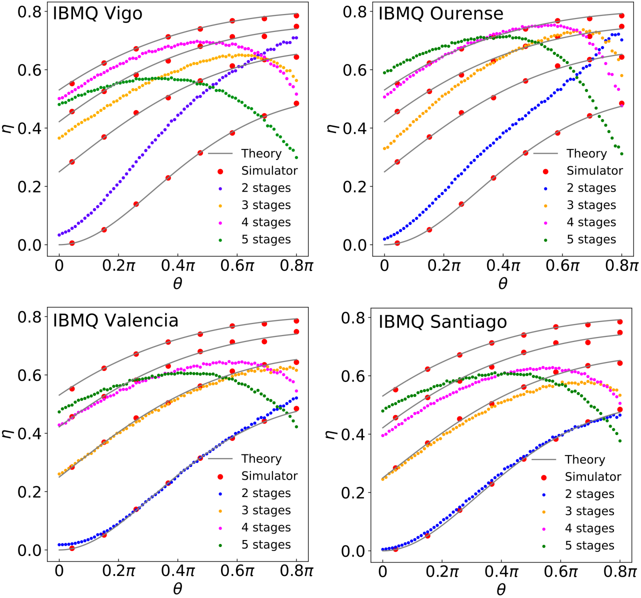

Figure 10: Running on different devices

1. Later devices show better results.
2. However, they all weren't accurate at 4 stages or above.

Hardy's paradox

Hardy's paradox

1. Hardy's paradox is a thought experiment in quantum mechanics devised by Lucien Hardy in 1992–3 in which a particle and its antiparticle may interact without annihilating each other.
2. The detection of a particle in d+ would indicate the presence of the obstructing particle, but without an annihilation taking place.

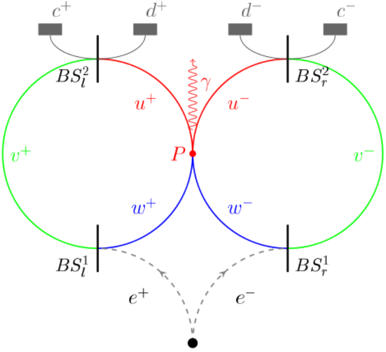

Figure 11: Hardy's paradox diagram. *Credit: Wikipedia*.

Hardy's paradox as interaction-free measurement

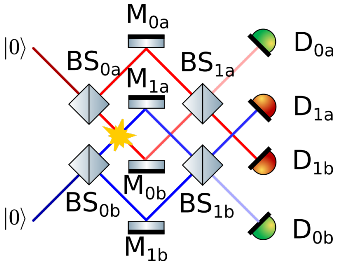

Figure 12: Optical diagram.

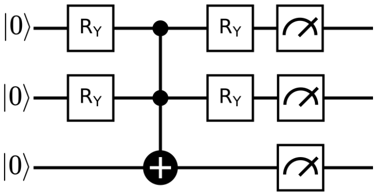

Figure 13: Quantum Circuit.

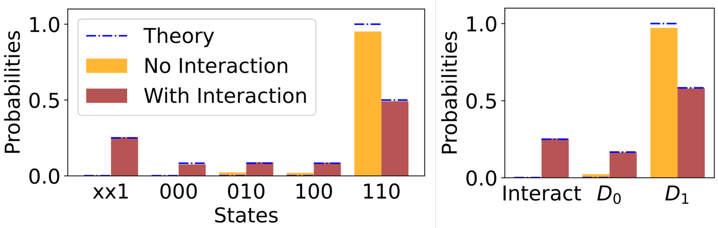

Figure 14: Running on IBMQ Athens.

Hardy's paradox and nonlocality

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Nonlocality for Two Particles without Inequalities for Almost All Entangled States

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tangled state can be written in the form (by Schmidt decomposition)

$$|\Psi\rangle = \alpha|+\rangle_1|+\rangle_2 - \beta|-\rangle_1|-\rangle_2, \tag{1}$$

where α and β are two real constants with

$$\alpha^2 + \beta^2 = 1. \tag{2}$$

The nonlocality proof pertains to the fraction $\gamma = |NA^2B^2|^2$ for which $D_1D_2 = 1$. Therefore the maximum nonlocal effect is when this fraction is maximum. Using the above expressions for A, B, and N we can write

$$\gamma = \left(\frac{(|\alpha| - |\beta|)|\alpha\beta|}{1 - |\alpha\beta|}\right)^2. \tag{20}$$

It is easily shown that this has a maximum value of $\frac{1}{2}(5\sqrt{5} - 11)$ (approximately 9%) when $2|\alpha\beta| = 3 - \sqrt{5}$, that is when

$$|\alpha|, |\beta| = 0.9070, 0.4211.$$

For these values we find (taking $|\beta|$ to be the larger number)

$$\theta_U = 68.54°, \quad \theta_D = -35.11° .$$

By considering the negative square root counterpart to Eq. (7), that is, by putting $\sqrt{\beta} \to -\sqrt{\beta}$, we find that we can also use $\theta_U = -68.54°$ and $\theta_D = 35.11°$ as we would expect from symmetry.

1. What is the 9% case in the circuit approach? How to demonstrate it?
2. Using the circuit approach, we can point out that:

$$\theta = \left[2\cos^{-1}\left(\sqrt{\frac{1}{2}\left(3 - \sqrt{5}\right)}\right)\right]$$

$$\approx 1.80911 \approx 0.576\pi.$$

3. The "nonlocality" state can be taken as the ratio of $|000\rangle$ to the other states.

Hardy's paradox on IBMQ

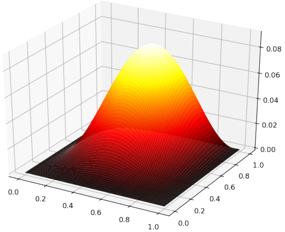

Figure 15: Theory.

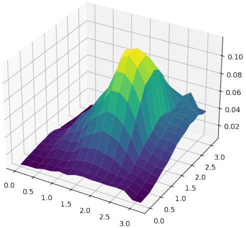

Figure 16: Vigo.

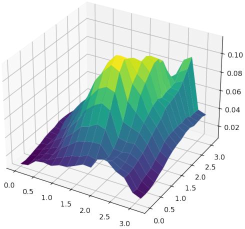

Figure 17: Ourense

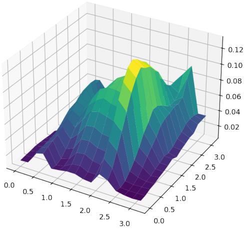

Figure 18: Santiago

Summary

Summary

1. Some interaction-free measurement schemes were executed on quantum computers, showing consistent results with previous findings.
2. Some improvement on the optical experiments were done. Subtle details are presented more explicitly using a different approach.
3. Later devices performed better than older ones, but they are generally not good enough yet to do these kind of simulation.

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Thank you for your attention!