Quantum Algorithms & Qiskit

Alexander J. Heilman

August 19, 2021

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First, the QFT

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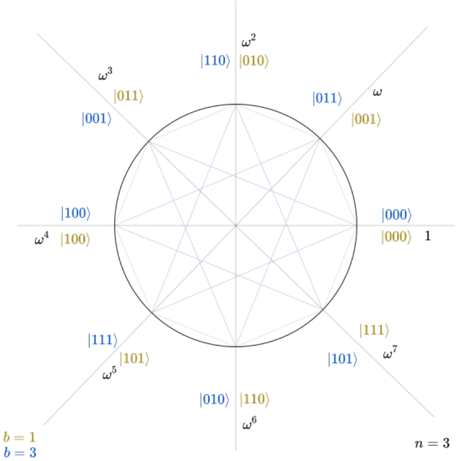

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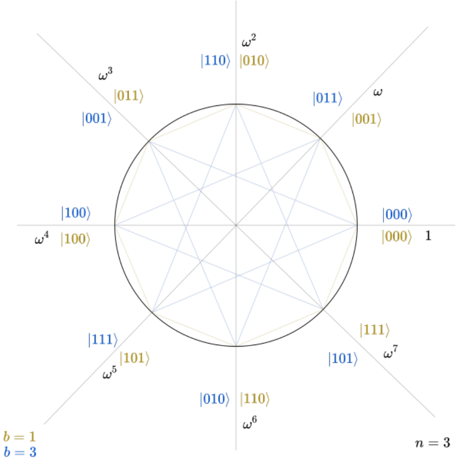

But how?

QFT: The gory details

The explict action of the n-qubit QFT on some given basis vector is

$$|j_1, \ldots, j_n\rangle \longrightarrow$$

$$\frac{\left(|0\rangle + e^{2\pi i 0.j_n}|1\rangle\right) \otimes \left(|0\rangle + e^{2\pi i 0.j_{n-1}j_n}|1\rangle\right) \otimes \ldots \otimes \left(|0\rangle + e^{2\pi i 0.j_1 \cdots j_n}|1\rangle\right)}{2^{n/2}}.$$

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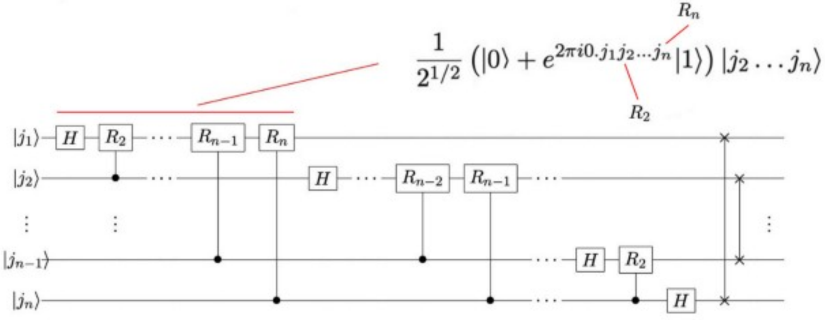

It's easier to see in matrix form

QFT: The gory details II

For $n = 3$ the QFT is

$$\frac{1}{2\sqrt{2}}\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & \omega & \omega^2 & \omega^3 & \omega^4 & \omega^5 & \omega^6 & \omega^7 \\ 1 & \omega^2 & \omega^4 & \omega^6 & 1 & \omega^2 & \omega^4 & \omega^6 \\ 1 & \omega^3 & \omega^6 & \omega & \omega^4 & \omega^7 & \omega^2 & \omega^5 \\ 1 & \omega^4 & 1 & \omega^4 & 1 & \omega^4 & 1 & \omega^4 \\ 1 & \omega^5 & \omega^2 & \omega^7 & \omega^4 & \omega & \omega^6 & \omega^3 \\ 1 & \omega^6 & \omega^4 & \omega^2 & 1 & \omega^6 & \omega^4 & \omega^2 \\ 1 & \omega^7 & \omega^6 & \omega^5 & \omega^4 & \omega^3 & \omega^2 & \omega \end{bmatrix}.$$

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Not so interesting yet, but it's usefulness will soon be found in phase estimation

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Phase Estimation takes some given unitary operator and an associated eigenvector and returns the corresponding eigenvalue.

$$\text{If } U|\psi\rangle = \lambda|\psi\rangle \quad \text{then} \quad U, |\psi\rangle \xrightarrow{PE} \lambda$$

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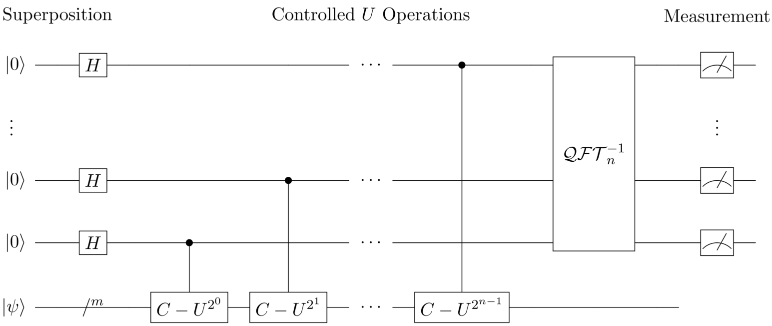

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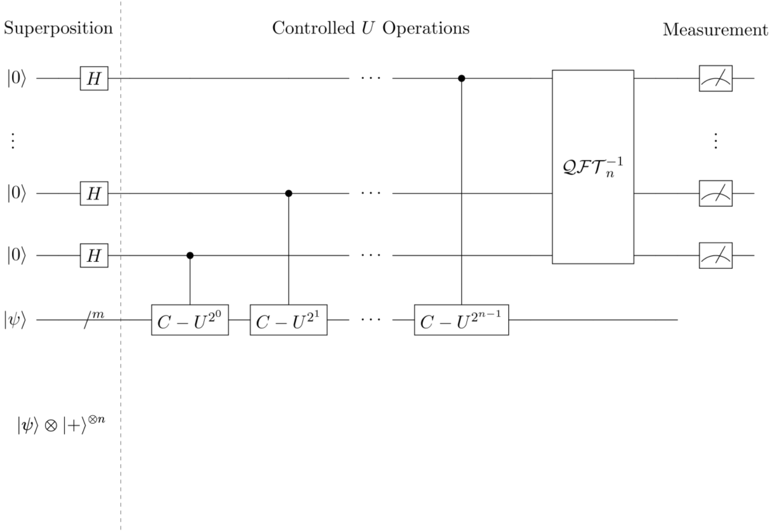

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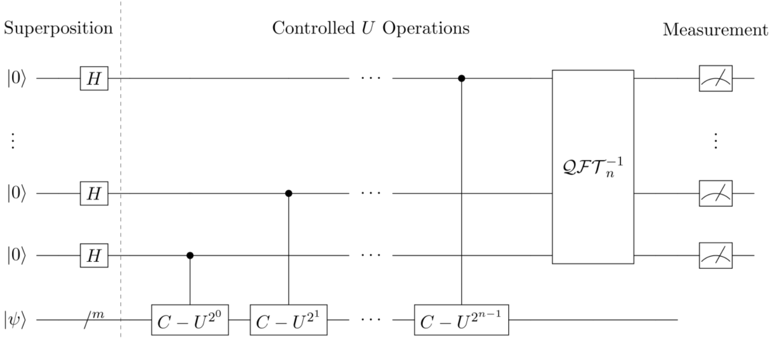

$$|\psi\rangle \otimes |+\rangle^{\otimes n} \to |\psi\rangle \otimes (|0\rangle + e^{i\alpha}|1\rangle) \otimes (|0\rangle + e^{2i\alpha}|1\rangle) \otimes \ldots \otimes (|0\rangle + e^{2^{n-1}i\alpha}|1\rangle)$$

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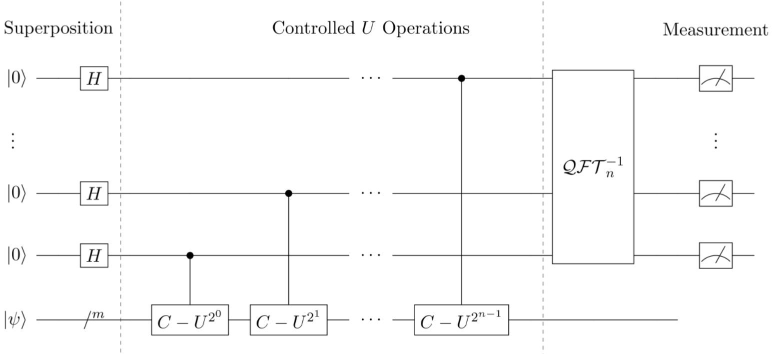
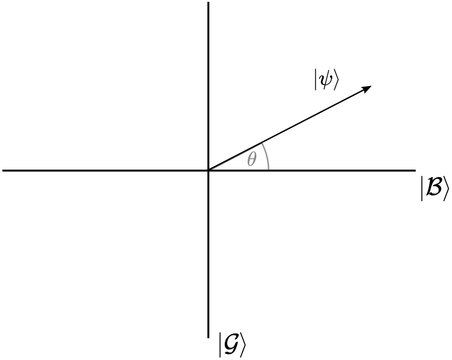


$|\psi\rangle \otimes |+\rangle^{\otimes n} \rightarrow$ $|\psi\rangle\otimes$ $(|0\rangle + e^{i\alpha}|1\rangle) \otimes (|0\rangle + e^{2i\alpha}|1\rangle)\otimes \ldots \otimes(|0\rangle + e^{2^{n-1}i\alpha}|1\rangle)$ $\rightarrow$ $|\psi\rangle \otimes |k\rangle$ with $\alpha = k\frac{2\pi}{2^n}$ and k an integer $mod\ 2^n$

Amplitude Amplification

Amplitude estimation takes some statevector partitioned into a good and a bad subspace



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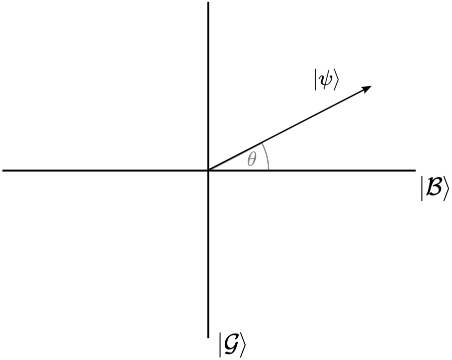

$$|\psi\rangle = sin(\theta)|\mathcal{G}\rangle + cos(\theta)|\mathcal{B}\rangle.$$

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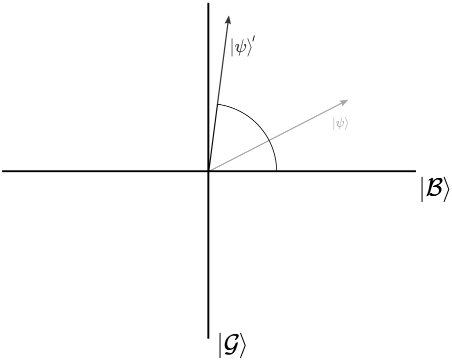

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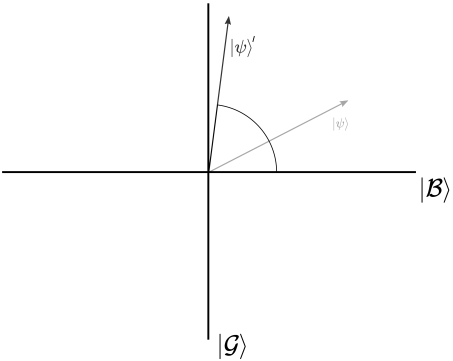

This is accomplished with consecutive applications of a special operator

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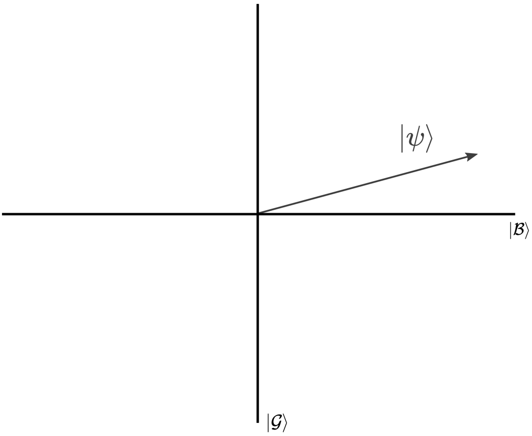
Let's see what they do!

Amplitude Amplification: Visualization I

First apply the operator $\mathcal{S}_{\mathcal{G}}$,



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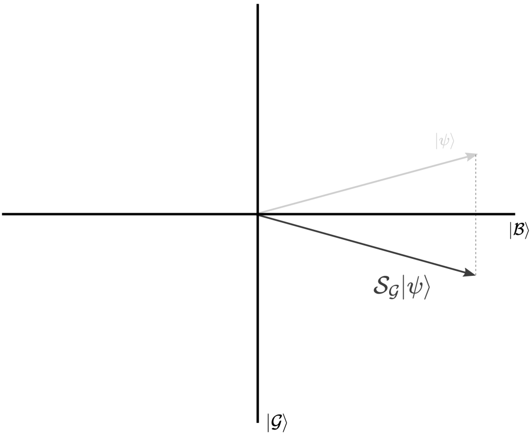

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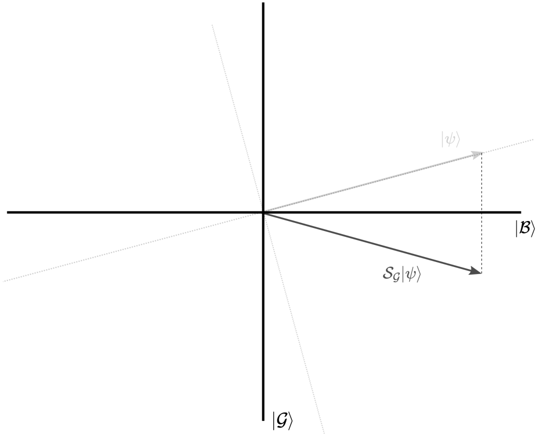

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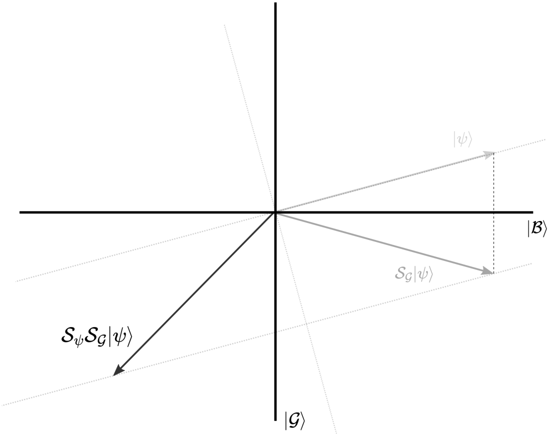

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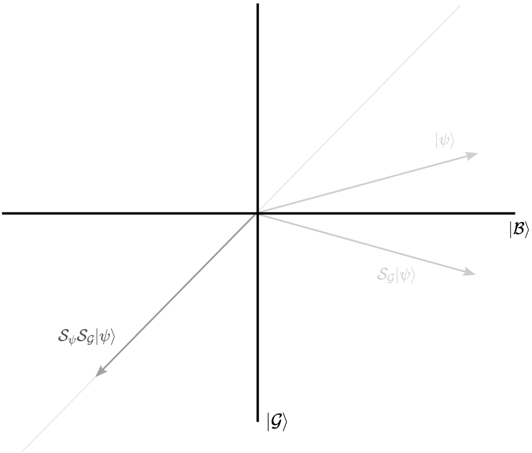

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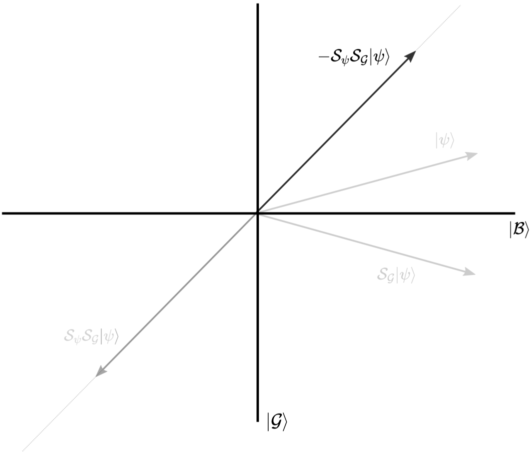

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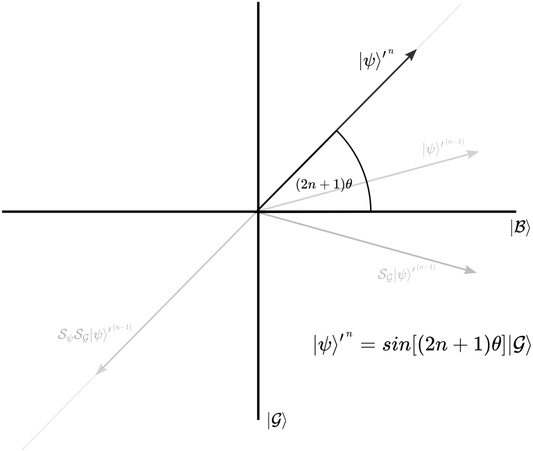

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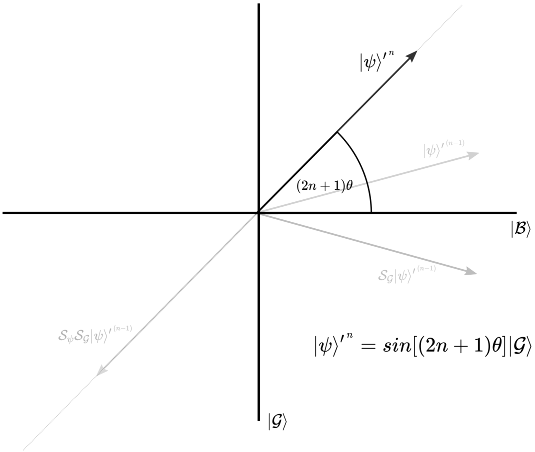

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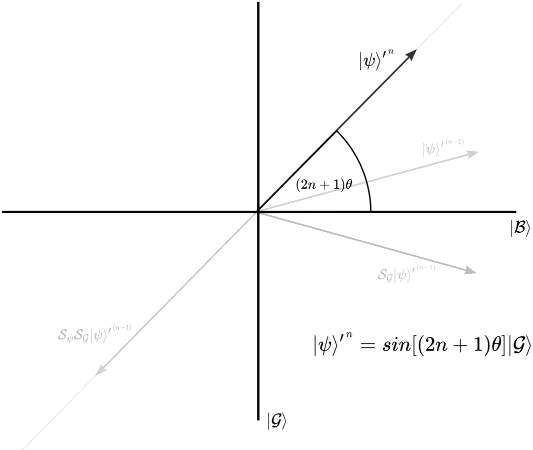

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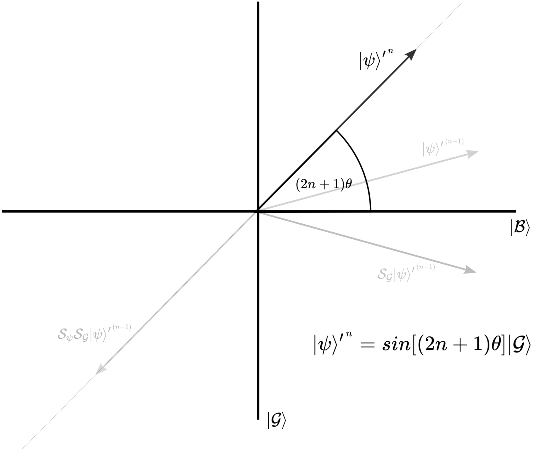

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Now, let's do some coding!

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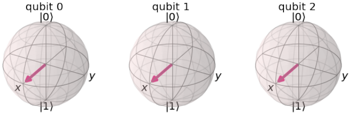
Input: $|000\rangle \rightarrow$ 

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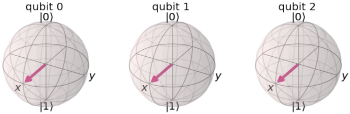

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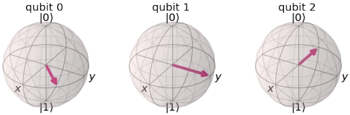

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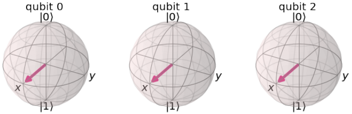

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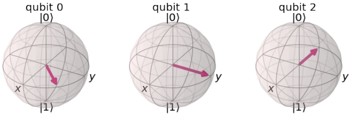

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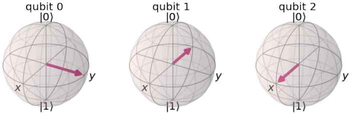

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Moving forward, I'll just link the code online.

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We already know that $|1\rangle$ is an eigenvector of basic phase gates.

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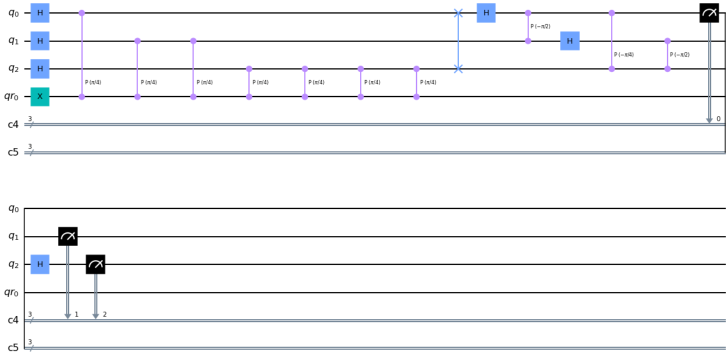

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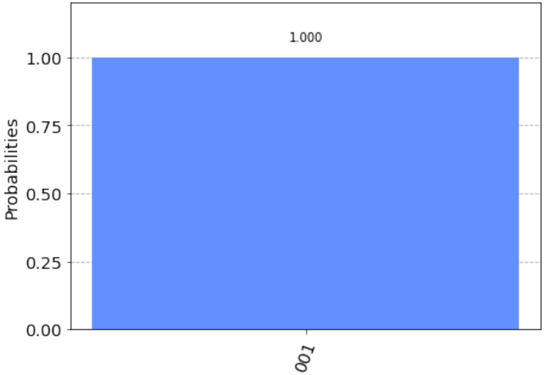

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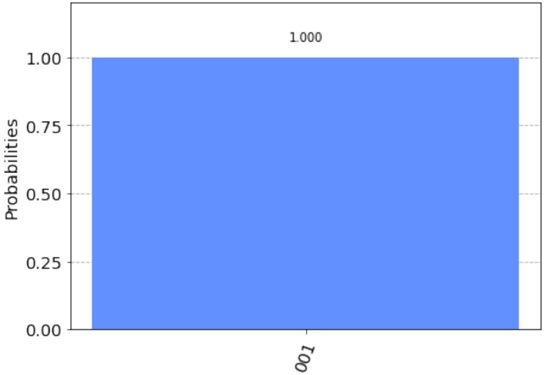

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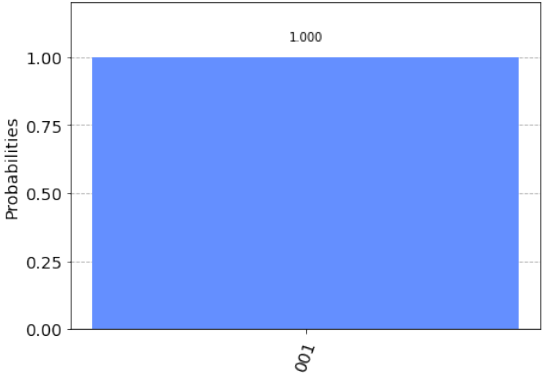

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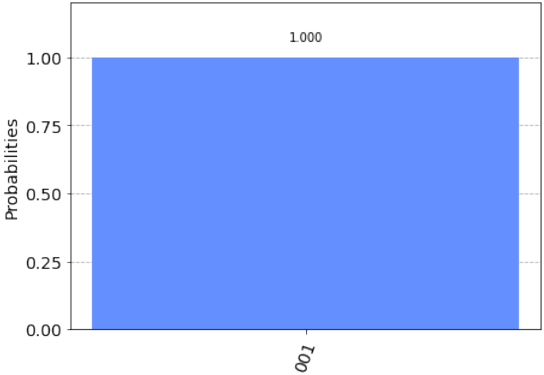

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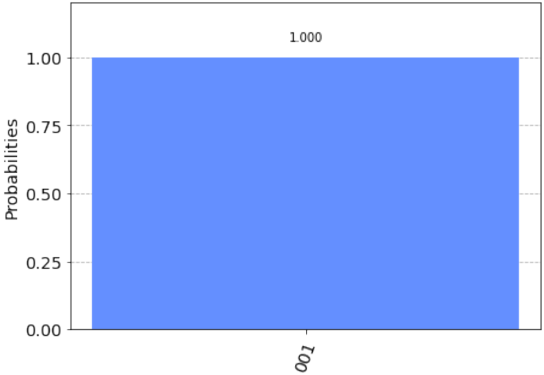
As the phase can be encoded perfectly in 3 qubits, we should expect the output vector to be $|k\rangle = |\alpha \frac{2^{n-1}}{\pi}\rangle$

Finding Phases: CP($\pi/4$)

Running the simulation gives a simulated measurement set:



Is this what we would expect? Yes!
As the phase can be encoded perfectly in 3 qubits, we should expect the output vector to be $|k\rangle = |\alpha \frac{2^{n-1}}{\pi}\rangle$ or $|001\rangle$ in binary

Finding Phases: CP($5\pi/4$)

Let's try it again with another ideal phase:

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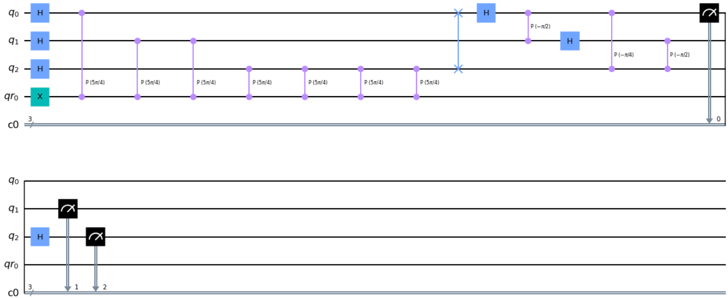

Finding Phases: CP($5\pi/4$)

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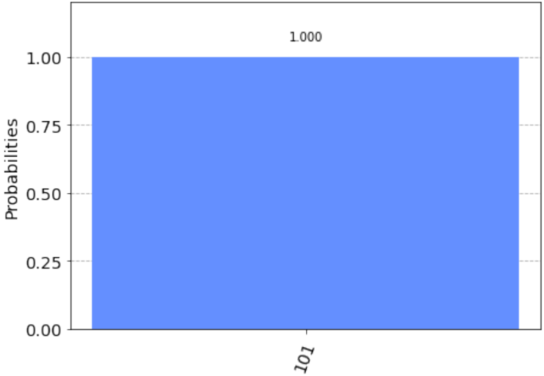

Yup!

Finding Phases: CP($4\pi/5$)

Let's try something that's not an ideal phase:

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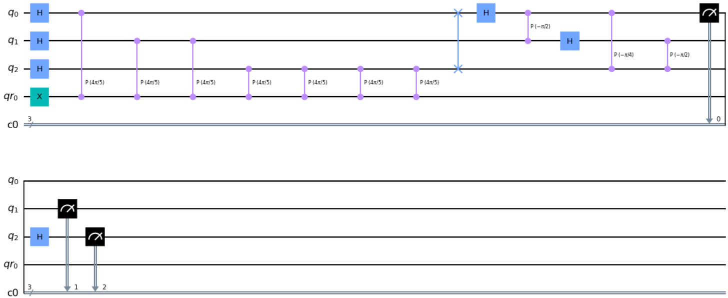

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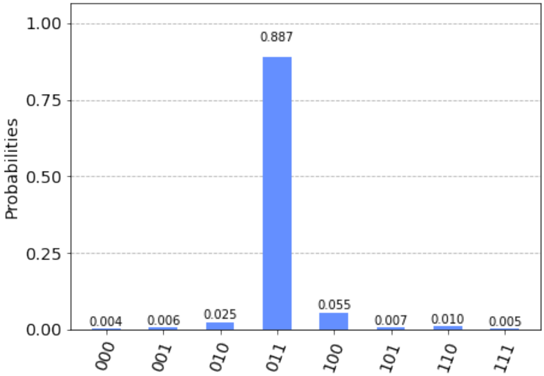

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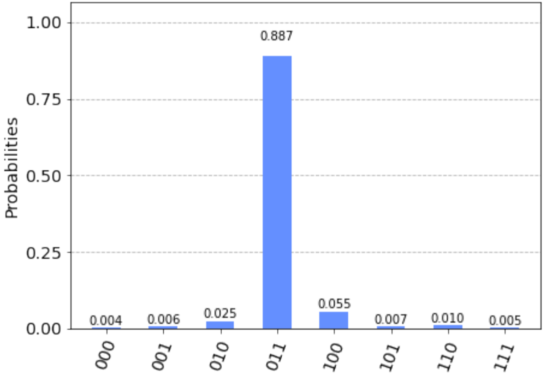

This seems to be a good estimate given $\frac{4\pi}{5}\frac{4}{\pi} = 3.2 \approx 3$.

Finding Phases: $CP(4\pi/5)$

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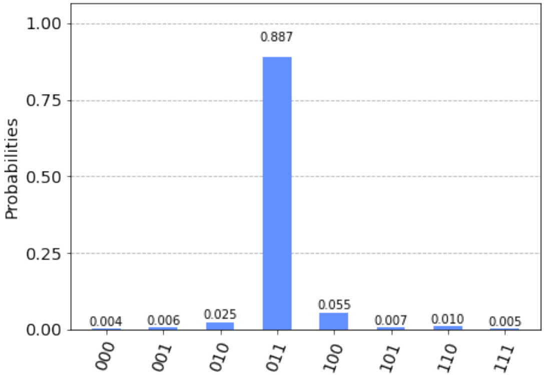

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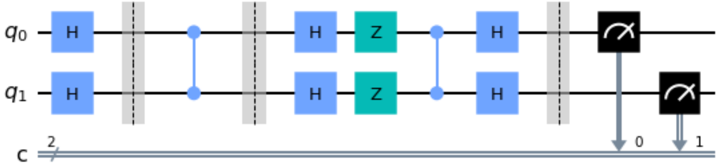
Let's do some amplification!

Amplitude Amplification in Practice

Below is a simple 2-qubit circuit for amplitude amplification that searches for the $|11\rangle$ state:



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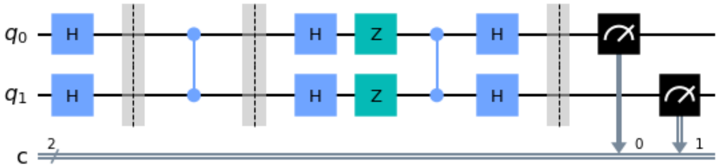

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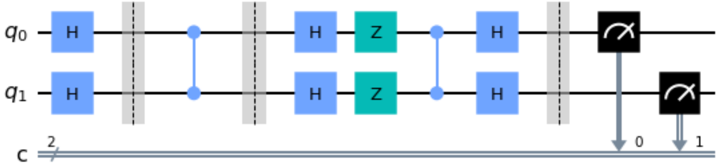

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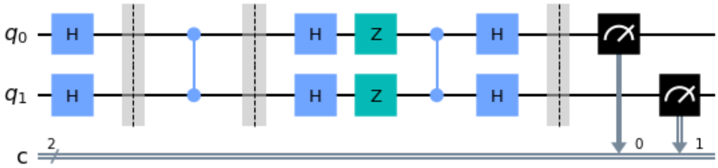

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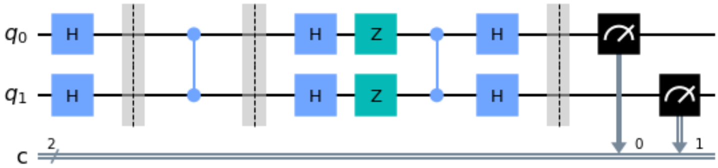

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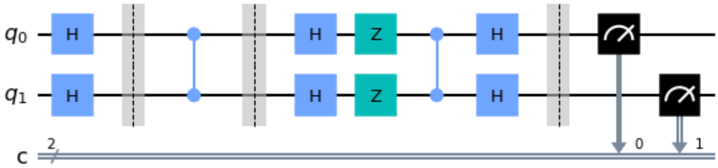

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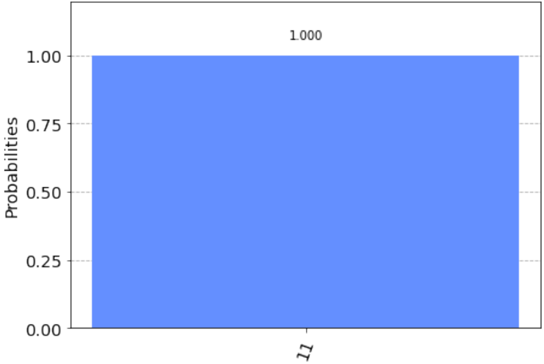
Let's run it!

Amplitude Amplification in Practice: Simulation

Running the previous circuit on the simulation we used for phase estimation:



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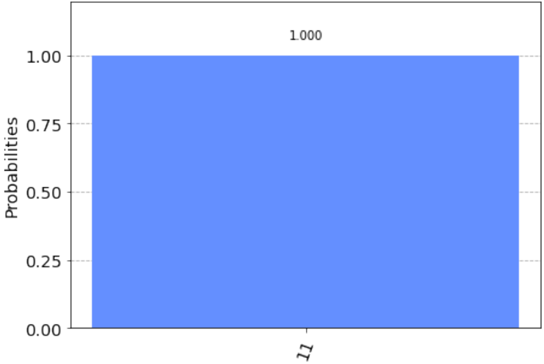

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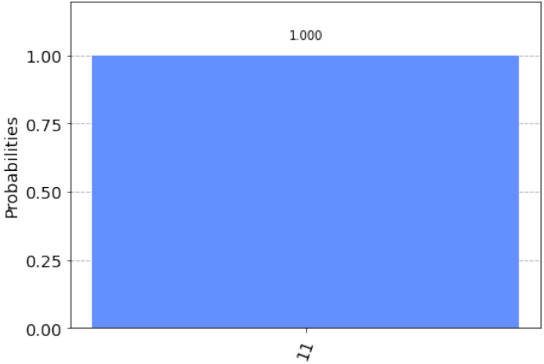

Perfect results! Let's run it for real!

Amplitude Amplification in Practice: Calling IBMQ

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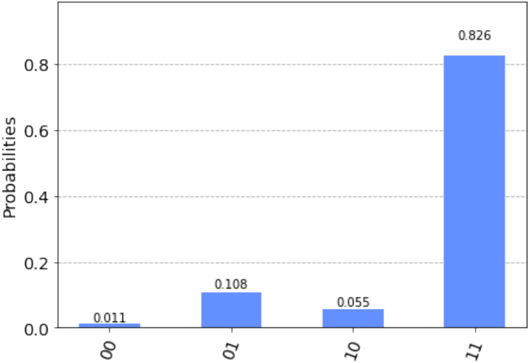

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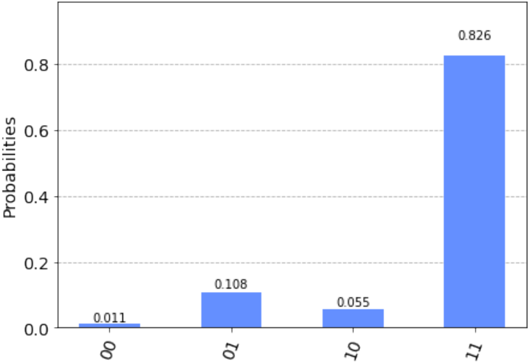

Not too bad!

Wrapping Up!

Basic Quantum Algorithms

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- Quantum Fourier Transform

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- Run circuits on real computers!

Moving Forward

Where to go from here?

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- Build to more complex applications

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Where to go from here?

- Build to more complex applications
- Extend to quantum machine learning
- Run some interesting experiments

That's it!

Notebooks for the circuits run here can be found at
`https://alexheilman.com`

References I

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[2] Michael A. Nielsen and Isaac L. Chuang. *Quantum Computation and Quantum Information: 10th Anniversary Edition*. 10th. USA: Cambridge University Press, 2011. ISBN: 1107002176.

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Thanks