qLearn Week 3: Quantum Operations

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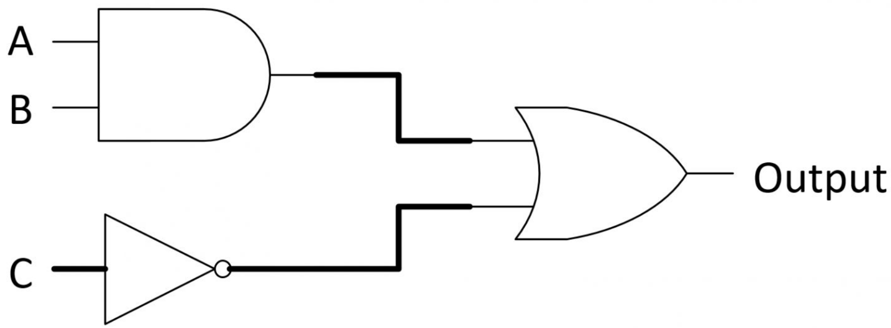
Last Week Recap

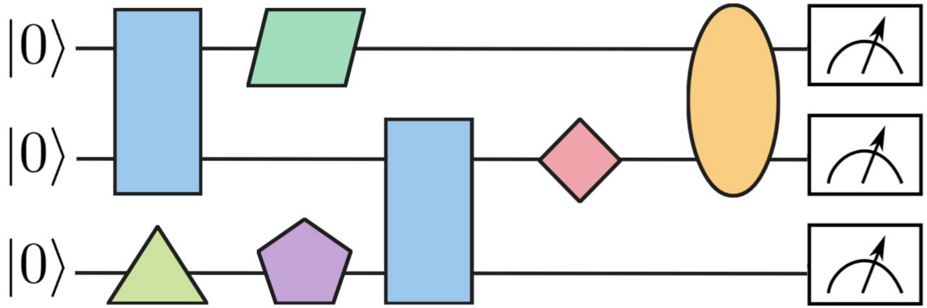
WHY LINEAR ALGEBRA?

Classical Circuits
- Boolean Logic

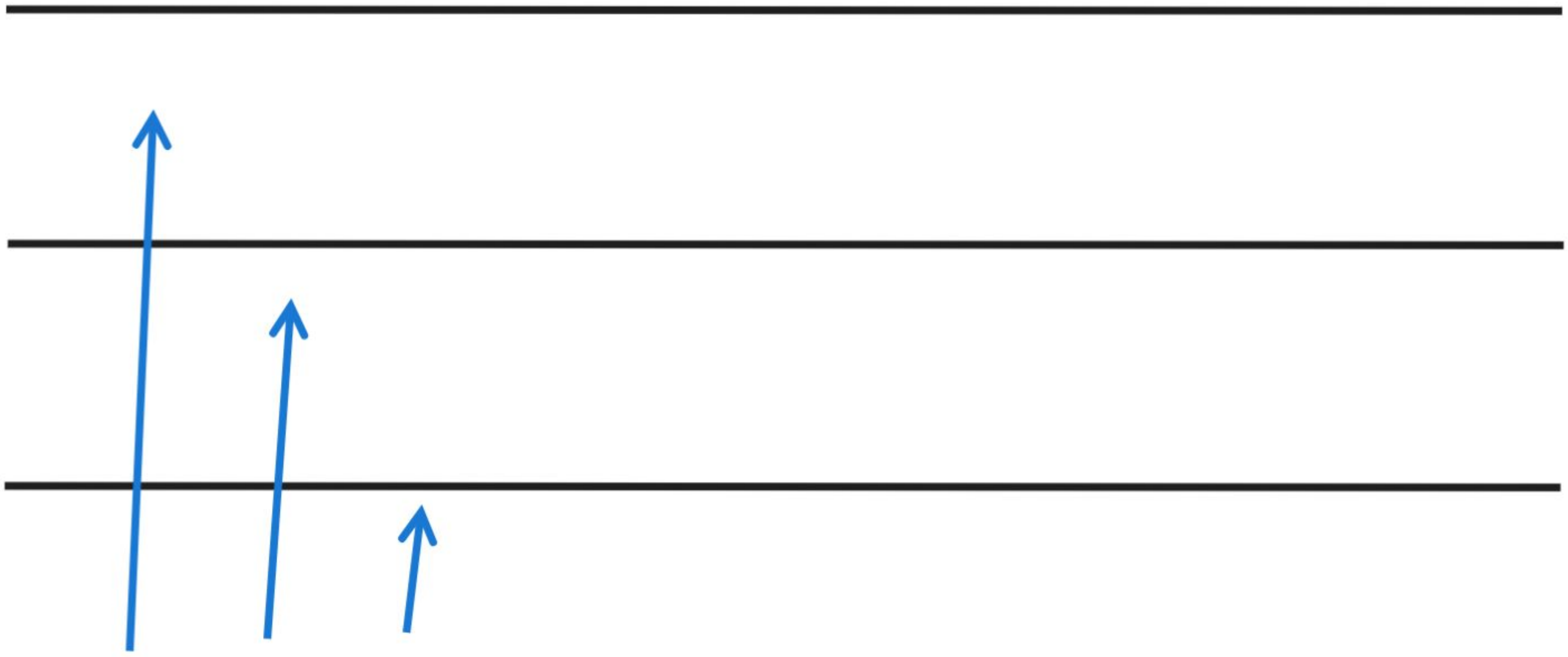


- Binary logic (0 and 1 inputs and outputs)
- **Physical** gates and wiring
- Different types of gates indicate different operations
- Every computer calculation and operation is a result of these circuits

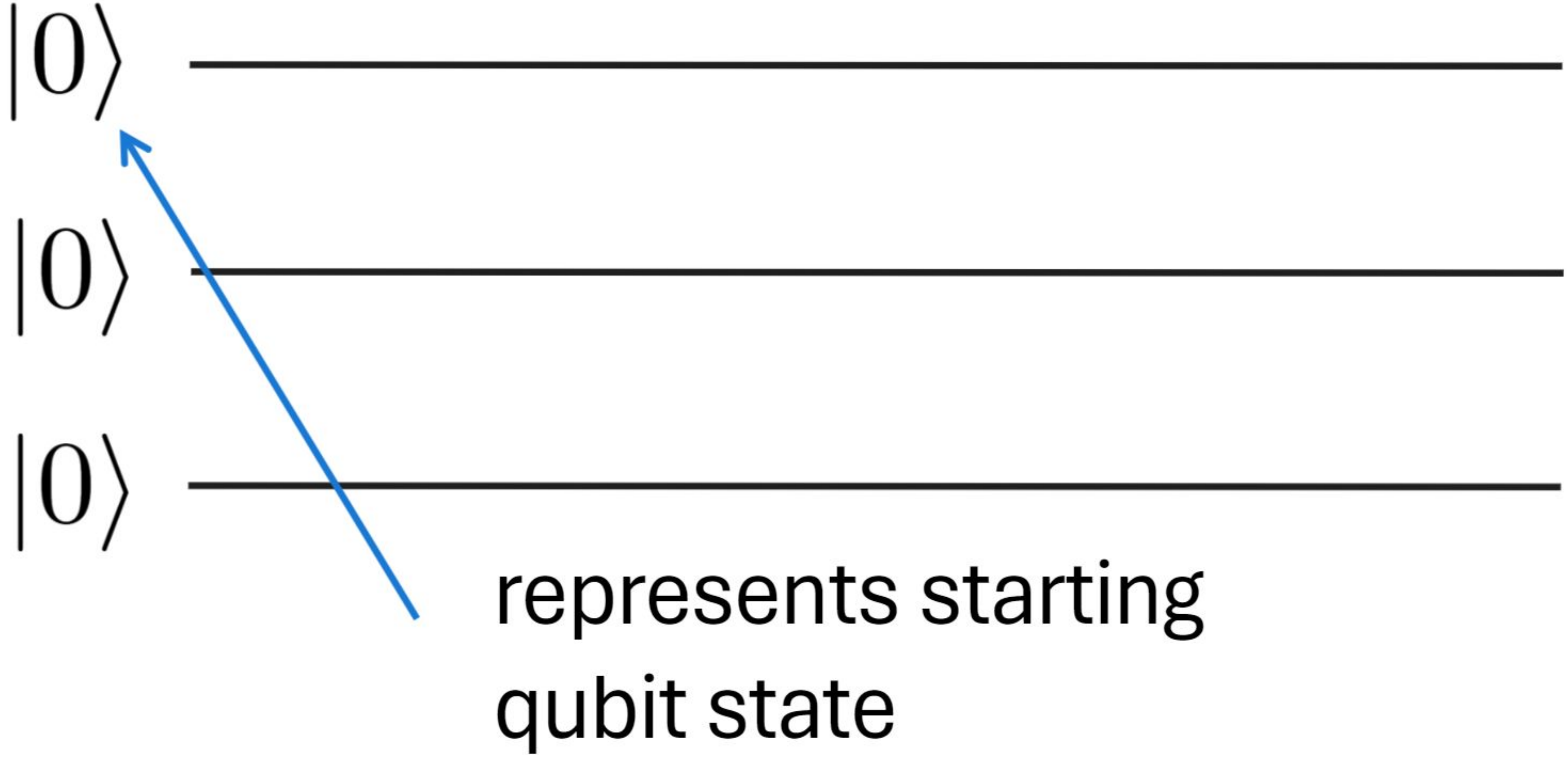
Quantum Circuits

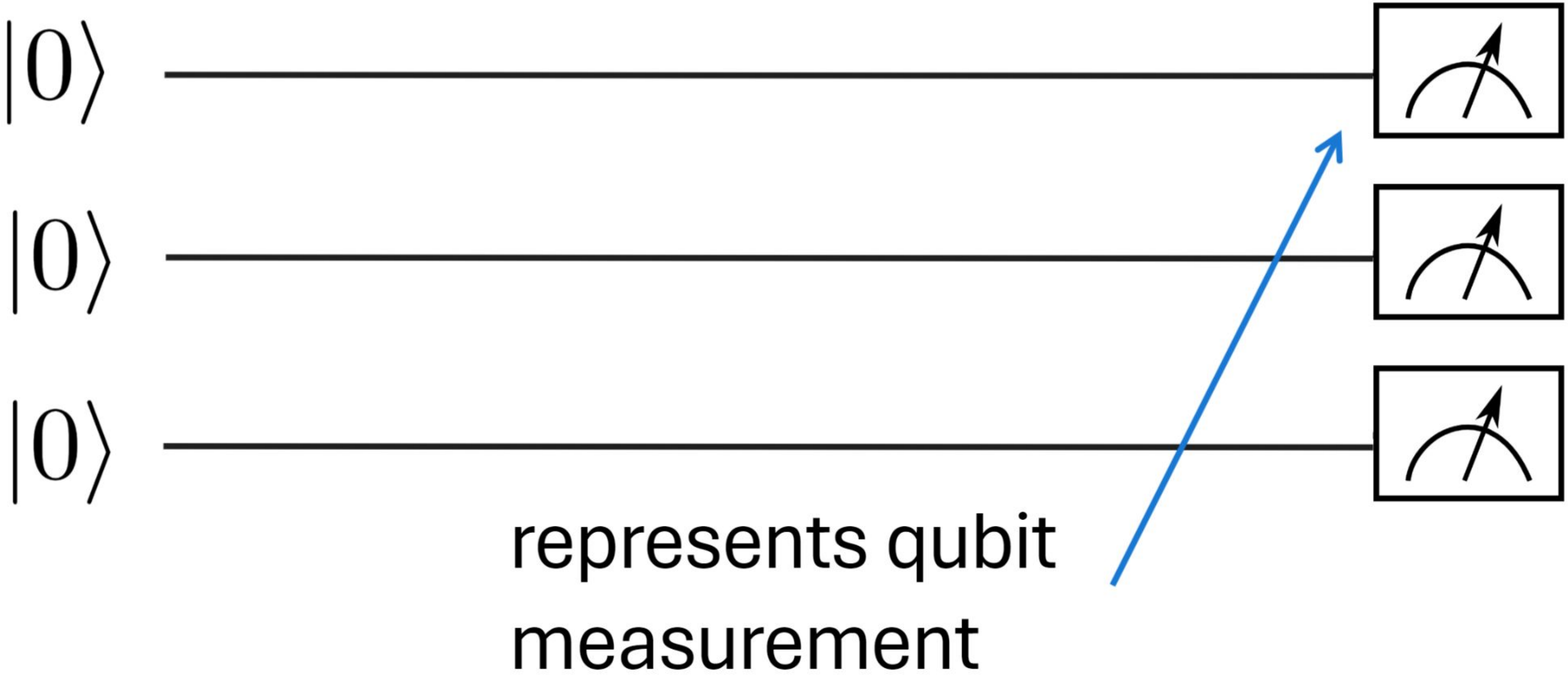


- **<u>Visual</u>** representation of operations being made on a qubit (very complicated physics, learn more in future hardware lectures)
- Represented by linear algebraic transformations mathematically
- Contains information about quantum algorithms, visual representation of them

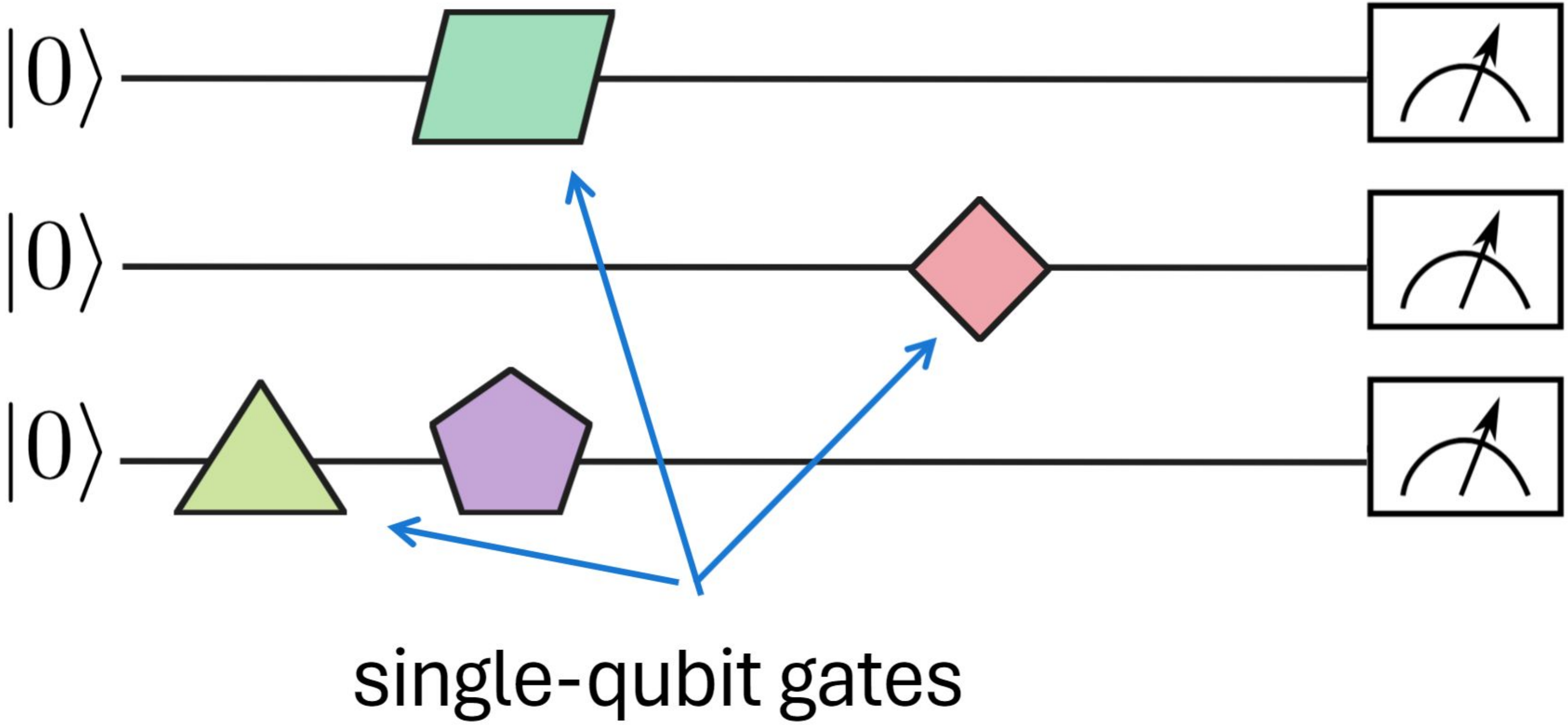


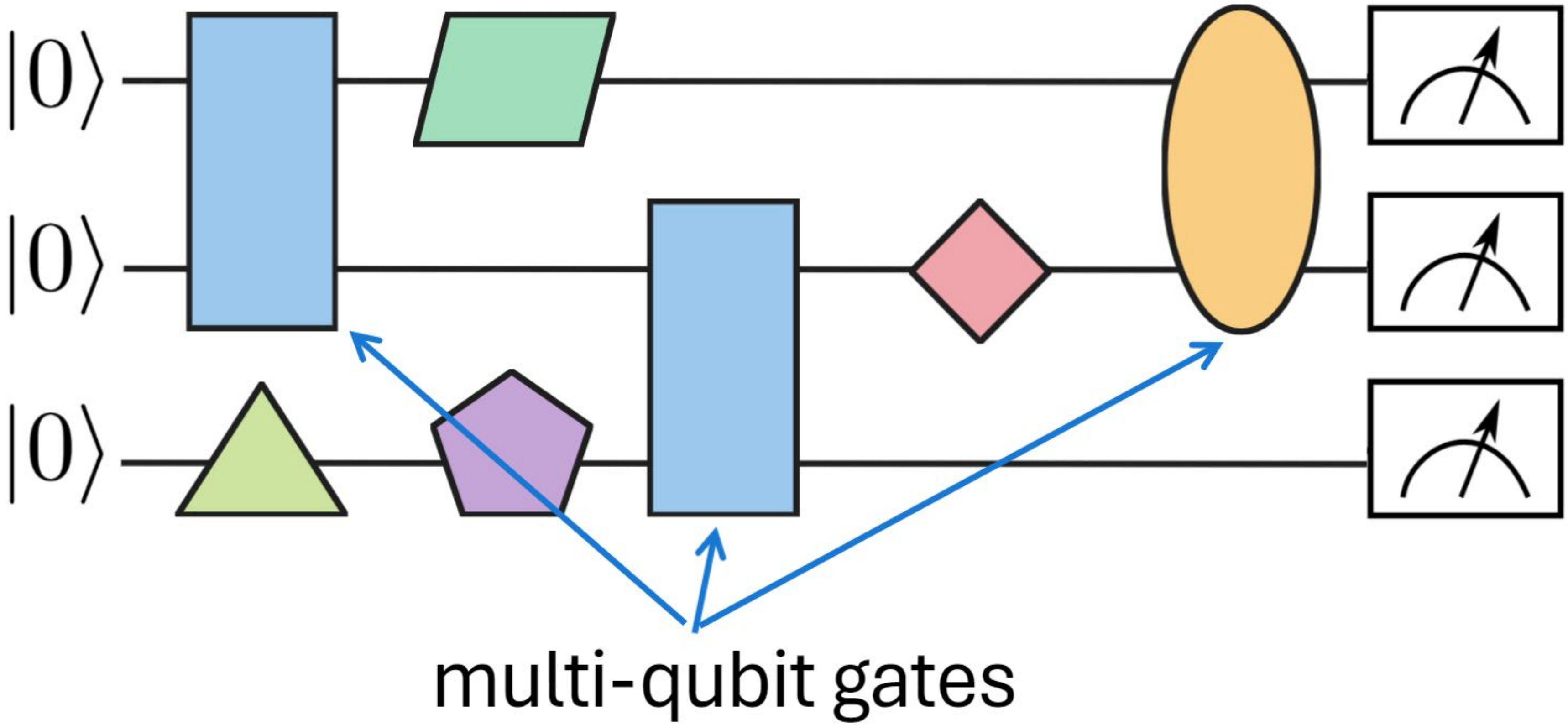
'wires' represent individual qubits

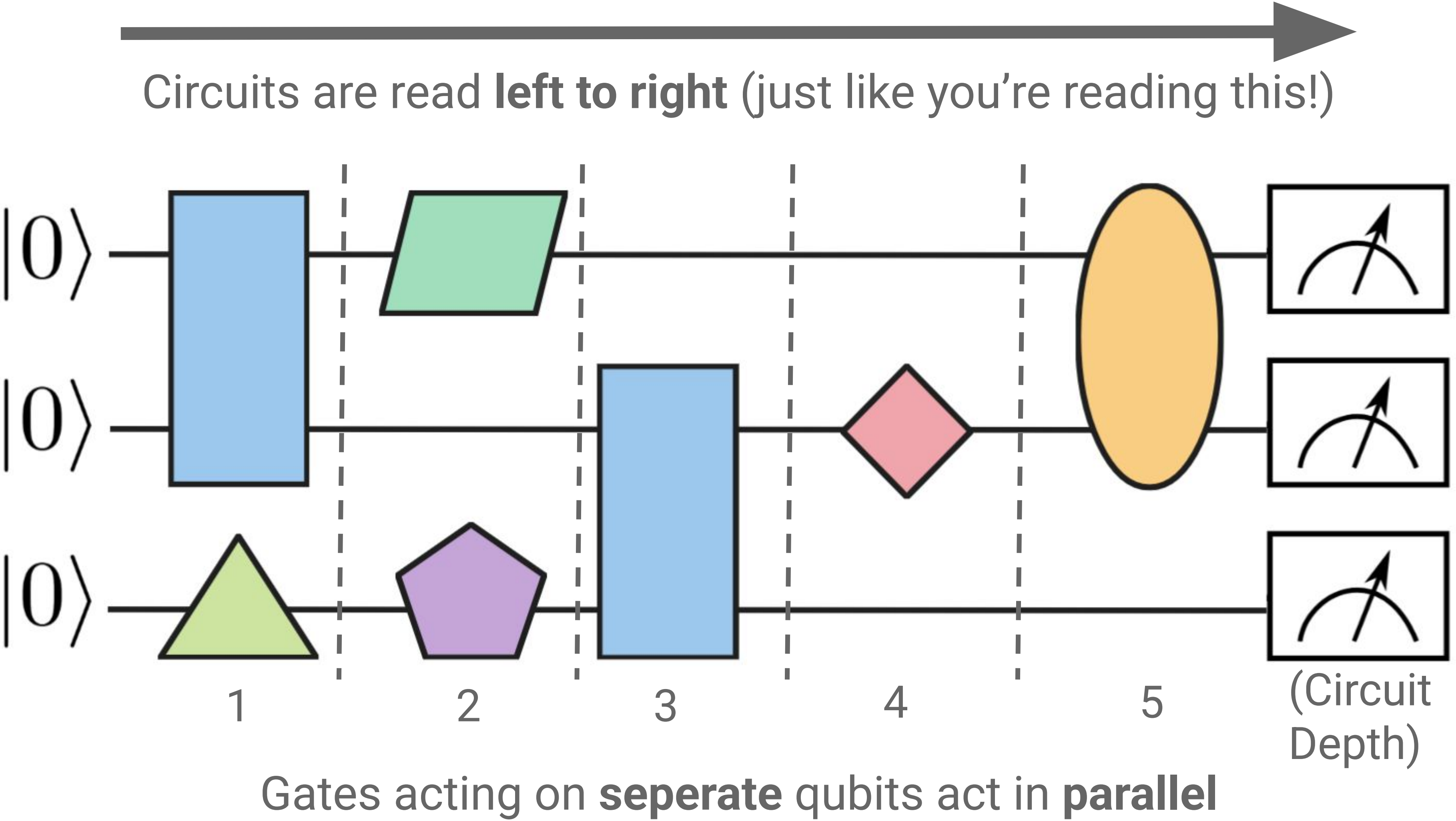

$|0\rangle$
$|0\rangle$
$|0\rangle$
represents starting qubit state

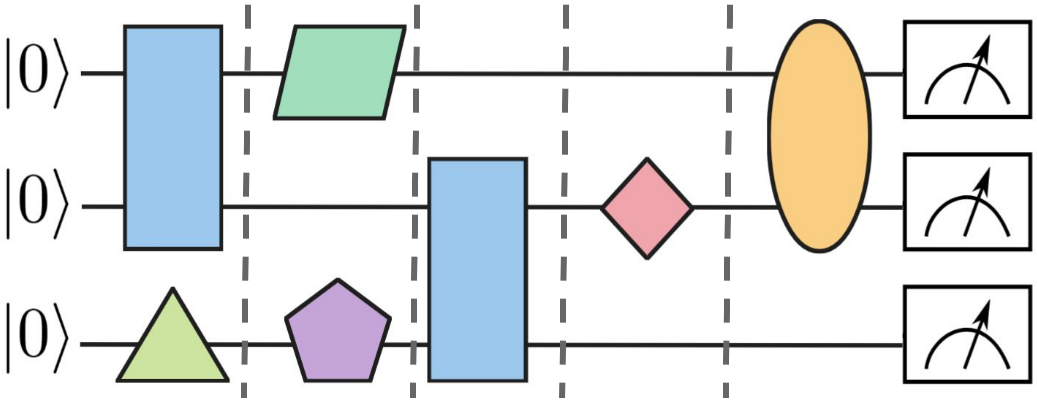


**NOTE: Does not always have to go at end of circuit!!! We will see examples later


$|0\rangle$
$|0\rangle$
$|0\rangle$
single-qubit gates

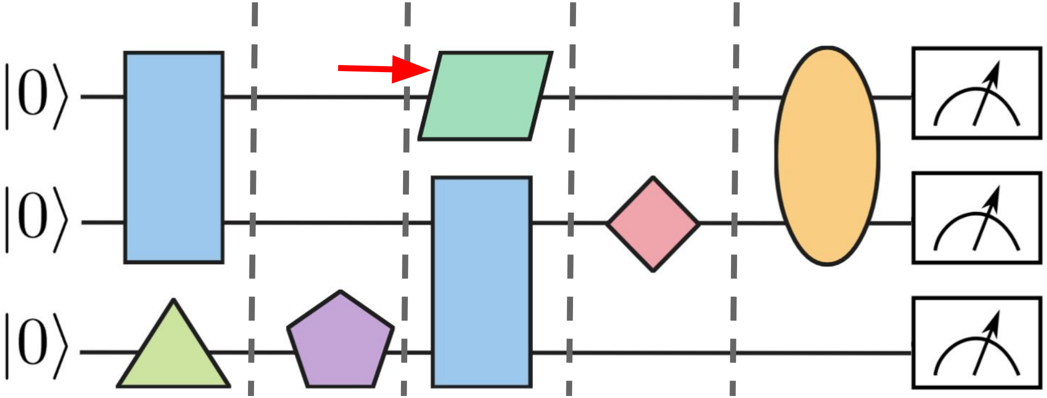

$|0\rangle$
$|0\rangle$
$|0\rangle$
multi-qubit gates


Circuits are read left to right (just like you're reading this!)
|0⟩
|0⟩
|0⟩
1
2
3
4
5
(Circuit Depth)
Gates acting on seperate qubits act in parallel



We do this for simplicity and resource conservation

Is **EQUAL** to



Recal: Unitary Matrices

Key Vocab:
1) Identity: Square matrix with 1s on diagonal and 0s elsewhere
2) Transpose^T: flipped matrix values over its diagonal
3) Conjugate* (for this lecture's sake): sign of imaginary part of a complex number is flipped

As previously mentioned, qubit operations are represented **mathematically** as **unitary matrices**

What is a unitary matrix and why do we use them?

- Qubit state vectors are normalized, as in they **always** have length 1
- Unitary matrices have special properties that, when applied to qubit state vectors, preserve their length

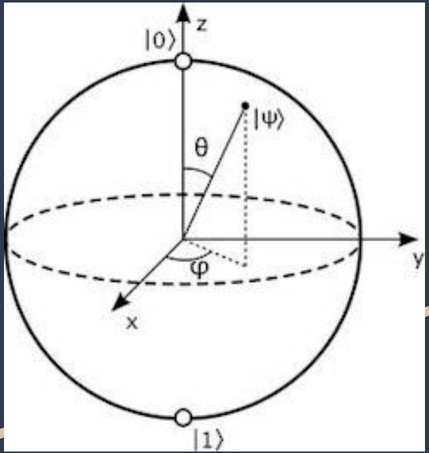
A $n \cdot n$ matrix U is unitary if

$$UU^\dagger = U^\dagger U = I_n$$

Where I_n represents the n-dimensional identity, and $U^\dagger$ is the notation for the conjugate transpose of U

How do these represent qubit transformations???

bloch.kherb.io



Parameterization of a unitary matrix!!

Proof: Representing a Unitary in Polar Form

For unitary with complex elements

$$U = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Write each element in their polar forms

$$a = e^{i\alpha}\cos(\theta/2), b = -e^{i(\beta-\gamma)}\sin(\theta/2)$$

$$c = e^{i\gamma}\sin(\theta/2), d = e^{i(\beta-\alpha)}\cos(\theta/2)$$

$$U = \begin{pmatrix} e^{i\alpha}\cos(\theta/2) & -e^{i(\beta-\gamma)}\sin(\theta/2) \\ e^{i\gamma}\sin(\theta/2) & e^{i(\beta-\alpha)}\cos(\theta/2) \end{pmatrix}$$

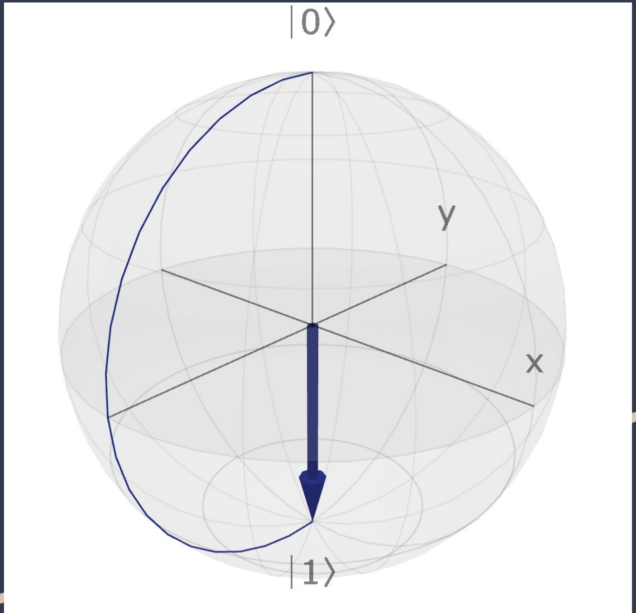
Using substitutions: $\phi = \beta - \alpha - \gamma, \omega = \gamma - \alpha$ (and phases)

We obtain:

$$U(\phi, \theta, \omega) = \begin{pmatrix} e^{-i(\phi+\omega)/2}\cos(\theta/2) & -e^{i(\phi-\omega)/2}\sin(\theta/2) \\ e^{-i(\phi-\omega)/2}\sin(\theta/2) & e^{i(\phi+\omega)/2}\cos(\theta/2) \end{pmatrix}$$

Single-Qubit Quantum Gates

Pauli X Gate



** Reversible (Hermitian, ask me what that means if you're reading this!)

-> Similar to a classical NOT Gate

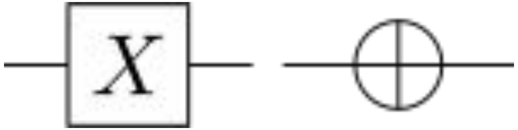
$$X|0\rangle = |1\rangle \qquad X|1\rangle = |0\rangle$$

For $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$$X|\psi\rangle = \alpha X|0\rangle + \beta X|1\rangle$$
$$= \alpha|1\rangle + \beta|0\rangle$$

-> Geometrically, 180° rotation around x-axis in Bloch sphere

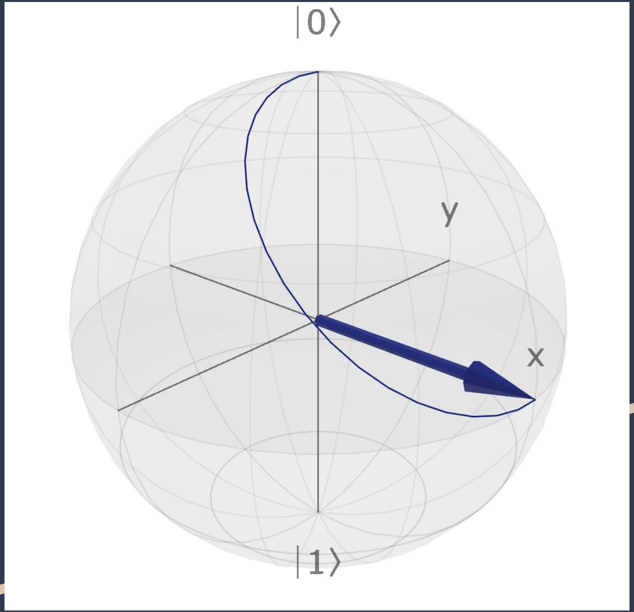
->Gate representation



-> Matrix representation

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

H (Hadamard) Gate



** Reversible

-> Creates a uniform superposition of states

$$H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |+\rangle$$

$$H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle$$

-> Geometrically, reflection over the diagonal of the XZ plane in Bloch sphere

->Gate representation

-> Matrix representation

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Code Break!

Reminder:

$$H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |+\rangle$$

$$H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle$$

A Note on Phases

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$
$$\alpha = ae^{i\theta}, \beta = be^{i\varphi}$$
$$|\psi\rangle = ae^{i\theta}|0\rangle + be^{i\varphi}|1\rangle$$
$$= e^{i\theta}(a|0\rangle + be^{i(\varphi-\theta)}|1\rangle)$$
$$= a|0\rangle + be^{i(\varphi-\theta)}|1\rangle$$

Global Phase:

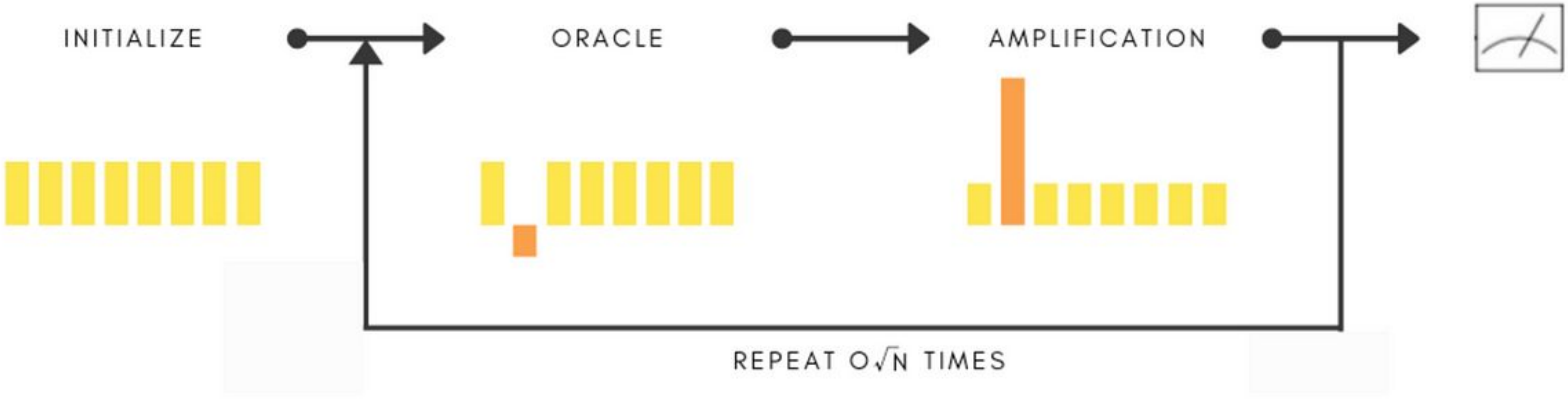
- Transformation that multiplies the entire state by a complex number of unit magnitude
- Note: No observable impact on measurement probabilities
- EX. $Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, YY = -I, YY|\psi\rangle = -|\psi\rangle$

Relative Phase:

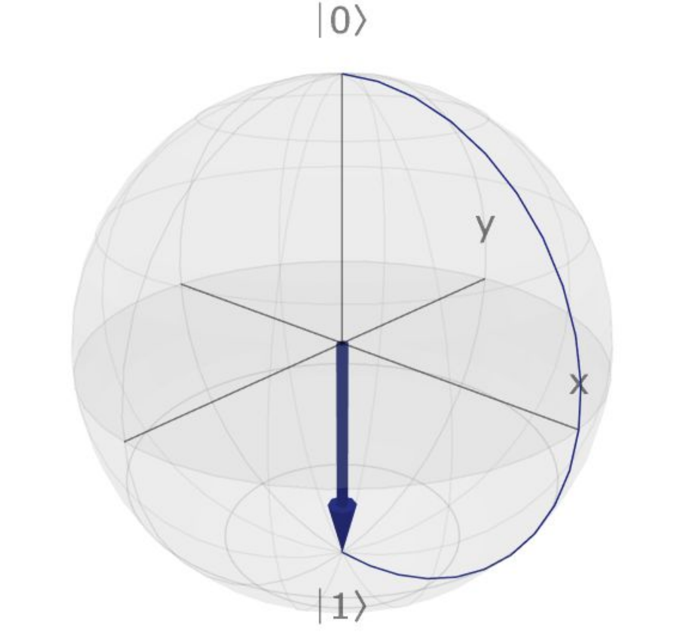
- Changes the phase relationship between the components of a superposition state
- Non-uniform impact on probabilities, thus affects measurement outcomes
- EX.

$$H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle$$

Example of Relative Phase Use in Algorithm



Pauli Y Gate



** Reversible

-> X, but adds **phase factors** +- i

$$Y|0\rangle = i|1\rangle$$
$$Y|1\rangle = -i|0\rangle$$

$$\text{For } |\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$
$$Y|\psi\rangle = \alpha Y|0\rangle + \beta Y|1\rangle$$
$$= \alpha(i|1\rangle) + \beta(-i|0\rangle)$$

-> Geometrically, 180° rotation around Y-axis

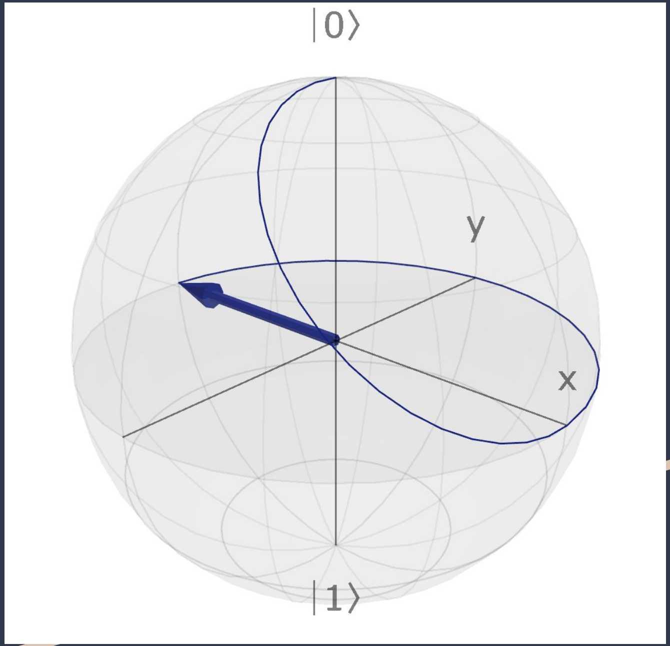
->Gate representation

$$-\boxed{Y}-$$

-> Matrix representation

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Pauli Z Gate



** Reversible

-> 'Flips' the phase of the state

$$Z|0\rangle \rightarrow |0\rangle$$

$$Z|1\rangle \rightarrow -|1\rangle$$

$$Z|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle$$

$$Z|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |+\rangle$$

-> Geometrically, 180° rotation around Z-axis

->Gate representation $-\boxed{Z}-$

-> Matrix representation

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Rotational Gates

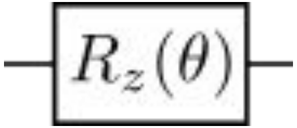
$$RX(\theta) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -i\sin(\frac{\theta}{2}) \\ -i\sin(\frac{\theta}{2}) & \cos(\frac{\theta}{2}) \end{bmatrix}$$

$$RY(\theta) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -\sin(\frac{\theta}{2}) \\ \sin(\frac{\theta}{2}) & \cos(\frac{\theta}{2}) \end{bmatrix}$$

$$RZ(\omega) = \begin{bmatrix} e^{-i\frac{\omega}{2}} & 0 \\ 0 & e^{i\frac{\omega}{2}} \end{bmatrix}$$

-> ‘Rotates’ the state around chosen axis

->Gate representation



-> Pauli Z: RZ(π)

-> Pauli Y: RY(π)

-> Pauli X: RX(π)

Special Cases

-> S is RZ($\pi/2$)

-> T is RZ($\pi/4$)

(Notice anything interesting? If we can rotate around all our axes, what does that mean)

Code Break!

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$RX(\theta) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -i\sin(\frac{\theta}{2}) \\ -i\sin(\frac{\theta}{2}) & \cos(\frac{\theta}{2}) \end{bmatrix}$$

$$RY(\theta) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -\sin(\frac{\theta}{2}) \\ \sin(\frac{\theta}{2}) & \cos(\frac{\theta}{2}) \end{bmatrix}$$

$$RZ(\omega) = \begin{bmatrix} e^{-i\frac{\omega}{2}} & 0 \\ 0 & e^{i\frac{\omega}{2}} \end{bmatrix}$$

Equivalent Gate Identities

$$U(\phi,\theta,\omega) = \begin{pmatrix} e^{-i(\phi+\omega)/2}\cos(\theta/2) & -e^{i(\phi-\omega)/2}\sin(\theta/2) \\ e^{-i(\phi-\omega)/2}\sin(\theta/2) & e^{i(\phi+\omega)/2}\cos(\theta/2) \end{pmatrix}$$

1) $H = Ry(\frac{\pi}{2})Rx(\pi)$

2) $Ry(\theta) = Rz(-\frac{\pi}{2})Rx(\theta)Rz(\frac{\pi}{2})$

3) $Rx(\theta) = Rz(\frac{\pi}{2})Ry(\theta)Rz(-\frac{\pi}{2})$

4) $Rz(\theta) = Ry(\frac{\pi}{2})Rx(\theta)Ry(-\frac{\pi}{2})$

5) $U(\phi,\theta,\omega) = Rz(\omega)Ry(\theta)Rz(\phi)$

Universal Gates

A set of gates is **universal** if any quantum computation can be approximated to arbitrary accuracy using **just gates from that set**

$$U(\phi, \theta, \omega) = Rz(\omega)Ry(\theta)Rz(\phi)$$

-> Example **universal single-qubit gates:**

- Hadamard (H) + T gate (pi/8 RZ gate)
- RX, RY, RZ

-> This has huge applications in hardware and error correction; we don't need a large breadth of instructions

Quantum Gates Cheat Sheet

See you next week!

-Multi-Qubit Operations
-Introduction to Quantum Utility