Qubit 101: What is Quantum Computing?

Linh Dinh

August 2025

DALHOUSIE UNIVERSITY

A Tour of Conventional Computing

Computing in the Modern World

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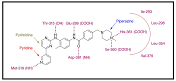

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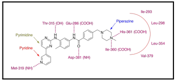

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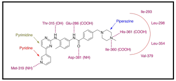

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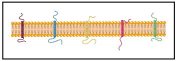

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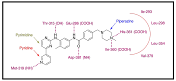

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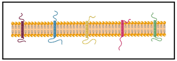
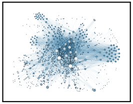


- As a framework for agent-based modeling in sociology.



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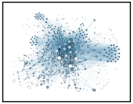

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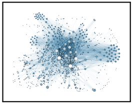

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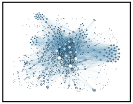

- Analyzing stone artifacts to determine their composition and use.

- Tracking the migratory patterns of wild animals.

The Limitation of Conventional Computing

Complex problems and more data to handle

$$\Downarrow$$

There are limits to what computers can do

$$\Downarrow \quad \text{Hype?}$$

Quantum Computing

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Quantum Computing

The Limitation of Conventional Computing

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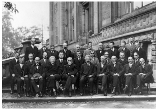
$\Downarrow$ Solution!

Quantum Computing

The Origins of Quantum Computing

Nature doesn't follow normal rules:

- Double-Slit Experiments (1800s–1920s):
  - Particles like electrons act like waves.
  - But if you check, they act like particles!



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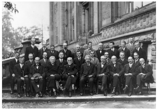

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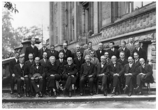

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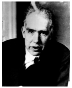
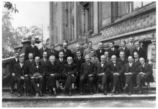
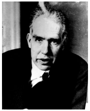
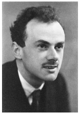
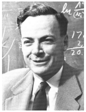
- Bohr's Atomic Model (1913):
  - Niels Bohr said electrons jump between specific energy levels in atoms, like steps on a ladder, not smoothly.



- It was very confusing for all the physicists involved.

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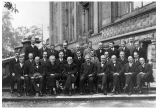  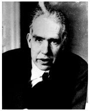 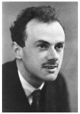  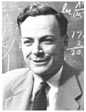

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The Strange World of Quantum Mechanics

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The Origins of Quantum Computing
Double Slits and Qubits
ZX to the Rescue
Some Remarks on Global Phase
Photo Credits

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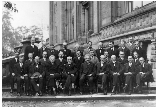

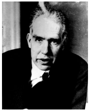
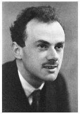

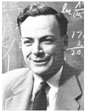

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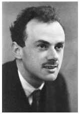
Einstein and Entanglement

You will learn more about this story in the afternoon.

The Dawn of Quantum Computing

- **1920s – 1930s**: Scientists such as Paul Dirac and Werner Heisenberg developed the math rules to understand the puzzling world of quantum mechanics.



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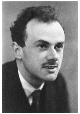

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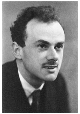

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However...

The rules were too tedious to work with by hand... They were even too tedious for computers!

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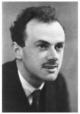

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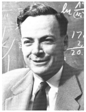
- **1930s – 1980s**: Playing by these rules, scientists were able to predict many phenomena, such as how chemicals interact.

- **1981**: Richard Feynman suggested building computers with quantum particles, since the particles already play by these rules.



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(**2001**) A real quantum computer by IBM and Stanford!

Applications of Quantum Computing

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So what can quantum computers do?

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- Recently, quantum machine learning has been gaining attention. The goal is to overcome the challenges of machine learning through the principles of quantum mechanics!

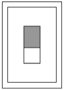
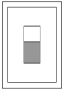
More Quantum Hype?

Is quantum machine learning the next big thing, or simply more quantum hype? Only time will tell!

Double Slits and Qubits

A Bit of Conventional Data

- You have probably heard that computers store data using bits. These are like light switches, you can turn them on or off. We will call on $|1\rangle$ and off $|0\rangle$.

$|0\rangle =$  $|1\rangle =$ 

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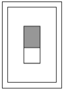
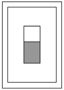
$|0\rangle =$  $|1\rangle =$ 

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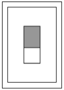
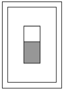
$|0\rangle =$  $|1\rangle =$ 

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Question Time!

What could we keep track of using a single bit? How about two bits?

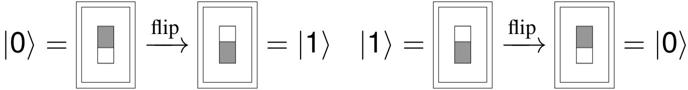
The Life of a Light Switch

Playing with Switches

Light switches are meant to be used! Can anyone think of an operation that we can apply to a light switch?

The Life of a Light Switch

- If we have a light switch, we can flip it! We can think of this as turning **false** into **true** and **true** into **false**. If something is **not true** then it is false, so we call this a NOT gate!



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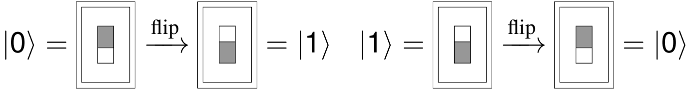

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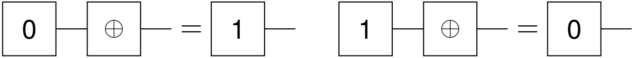

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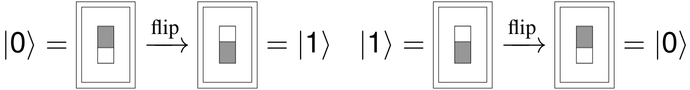

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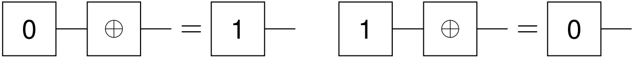
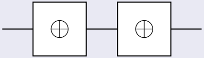


Exercise Time!

Do you think that  is the same as —?

Introducing the Qubit

Now to the exciting part: what is a qubit?

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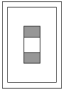 $= |?!\rangle$

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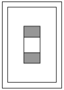

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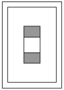

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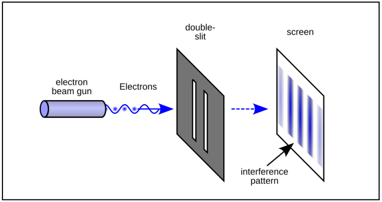
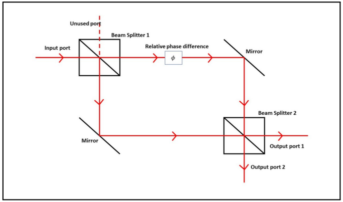
- Quantum computing replaces bits with *qubits* made from quantum particles. This isn't science fiction, it's real!
- A qubit can be anywhere between $|0\rangle$ and $|1\rangle$, though this is better thought of as being partly $|0\rangle$ and $|1\rangle$ at the same time. We call this *quantum superposition*!

Double Slits Experiment





Double Slits and Qubits

The electrons in the double slit experiment are qubits.

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A Quantum NOT Gate?

What would it mean to apply a NOT gate to the electron in the double slit experiment? Does our light switch analogy work anymore?

Double Slits and Qubits

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- The qubit is in state $|0\rangle$ if it goes through the first slit.
- The qubit is in state $|1\rangle$ if it goes through the second slit.
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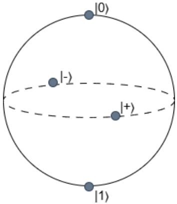
Experiments have shown that qubits have many ways to be between $|0\rangle$ and $|1\rangle$. We can visualize these superpositions as points on a ball (the Bloch sphere).



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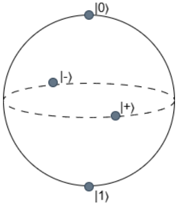
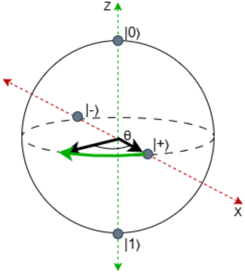


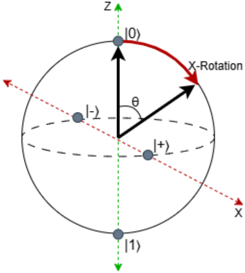
The NOT Gate Revisited

Is there a way to do the NOT gate without moving $|+\rangle$ and $|-\rangle$? What sort of rotation would this be?

Spinning the Bloch Sphere

In quantum computing, we care about two special kinds of rotations: the Z-rotations and the X-rotations.





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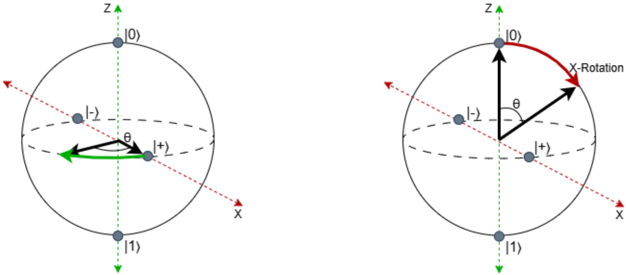

Is This Enough?

Using only the Z-rotations and the X-rotations, is it possible to rotate the Bloch sphere in every possible way?

ZX to the Rescue

ZX-Calculus: Background

If we would like to jump into the world of quantum computing, we will need to know the rules of the game. Unfortunately, the rules developed in the early 1900s are very tedious...

$$(\sigma_Z \otimes I) \circ (I \oplus \sigma_X) \circ (\sigma_X \oplus I) \circ (I \oplus \sigma_X) \circ (I \otimes \sigma_Z) = \text{SWAP}$$

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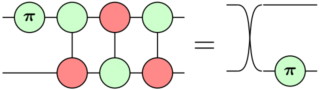

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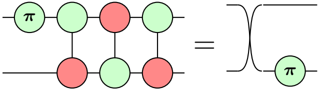

Let's spend some time learning what this tells us about qubit states.

ZX-Calculus: Qubit States

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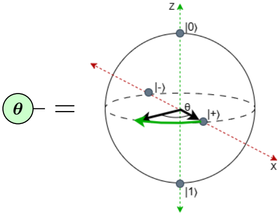

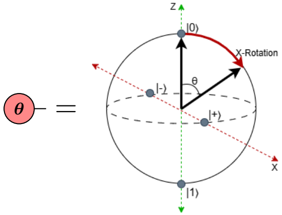

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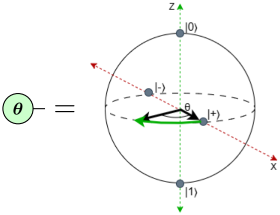
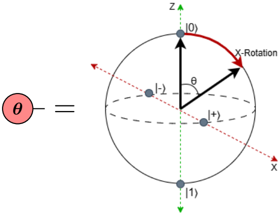
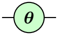
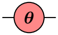




Check Your Understanding

What are (π)– and (π)–? What are (2π)– and (2π)–?

ZX-Calculus: Learning the Rules

What if we want to want to take a qubit and rotate it? We write the rotations like  and . To rotate the state, we simply join the two dots together!

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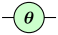
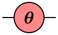
What if we want to want to take a qubit and rotate it? We write the rotations like 

and 

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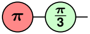

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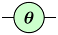
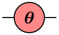
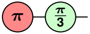
What if we want to want to take a qubit and rotate it? We write the rotations like  and . To rotate the state, we simply join the two dots together!

 rotates $|1\rangle$ by $(\pi/3)$-radians about the Z-axis.

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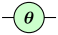
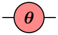
What if we want to want to take a qubit and rotate it? We write the rotations like 

and 

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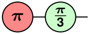

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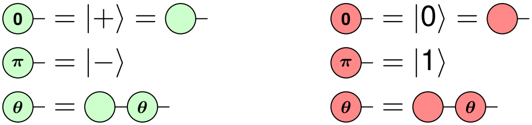

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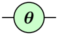
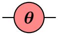
What if we want to want to take a qubit and rotate it? We write the rotations like 

and 

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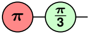

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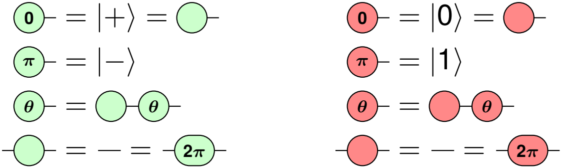

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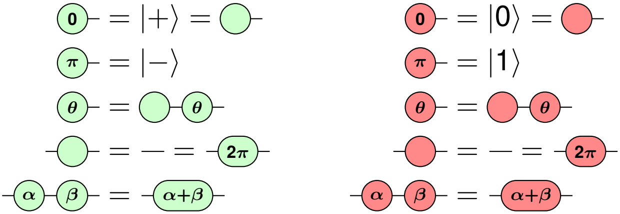

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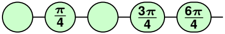

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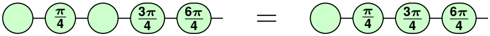

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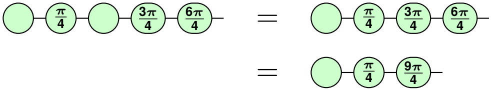

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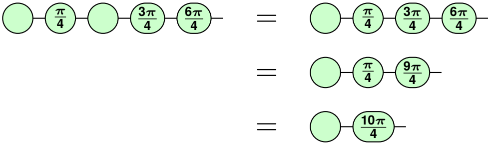

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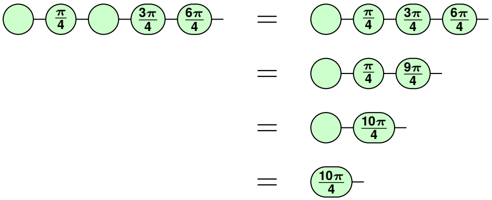

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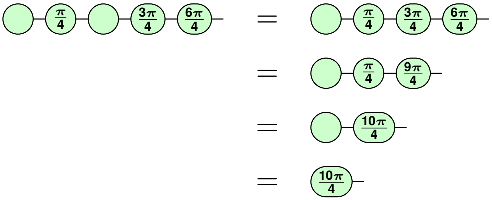

Are We Done Yet?

We should be careful. What happens if we rotate the Bloch sphere by $2\pi = 8\pi/4$ radians?

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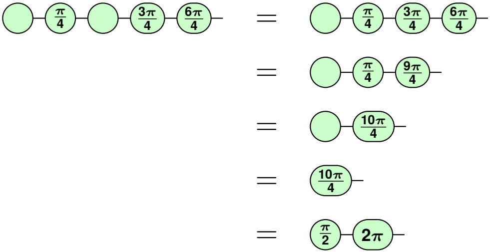

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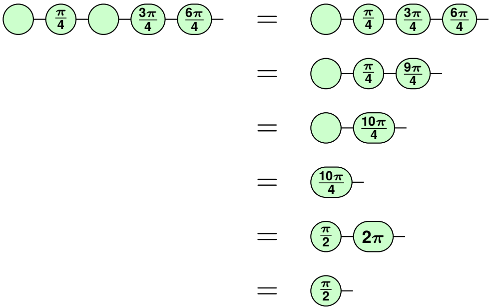

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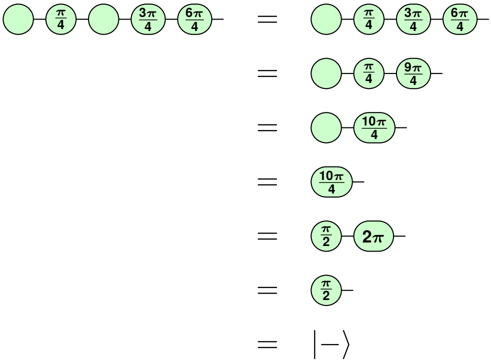

Preparing a Superposition State

States that fall half-way between $|0\rangle$ and $|1\rangle$ on the Bloch sphere, such as $|+\rangle$ and $|-\rangle$, are very important is quantum computing. However, we usually start with all of our qubits in the state $|0\rangle$.

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Is it possible to switch $|0\rangle$ with $|+\rangle$ and $|1\rangle$ with $|-\rangle$. This would give us easy access to both superpositions.

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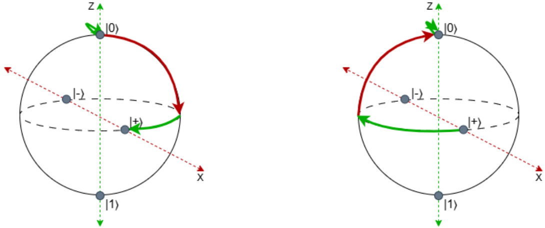
This turns out to be tricky, but possible!



The Hadamard Gate

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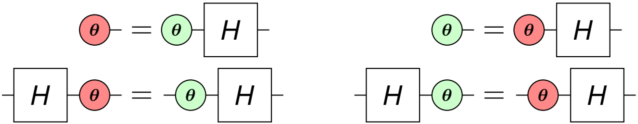
Intuitively, the Hadamard gate lets us swap the colours of dots.



Oh no! NOT Again!

Remember for earlier in this lecture that the controlled NOT gate is the same as the —(π)— rotation.

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Remember for earlier in this lecture that the controlled NOT gate is the same as the $-(\pi)-$ rotation.

Not a Superposition?

What would the NOT gate do to $-(\theta)-$?

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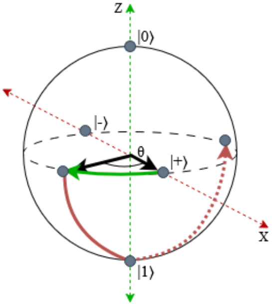
To understand how Z-rotations and X-rotations interact, it might help to look at what happens on the Bloch sphere.



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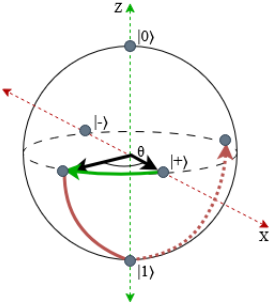
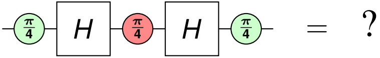


Playing with the Bloch sphere, we can confirm that –(θ)–(π)– is the same as –(π)–(−θ)–. You can try this on your own over one of the breaks.

Example: A Hadamard Colour Change



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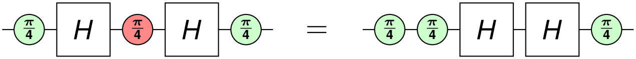

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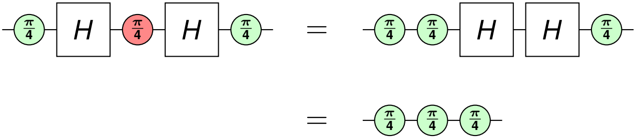

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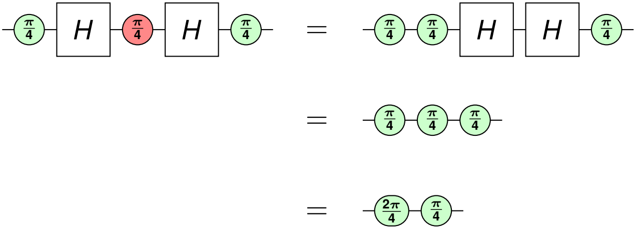

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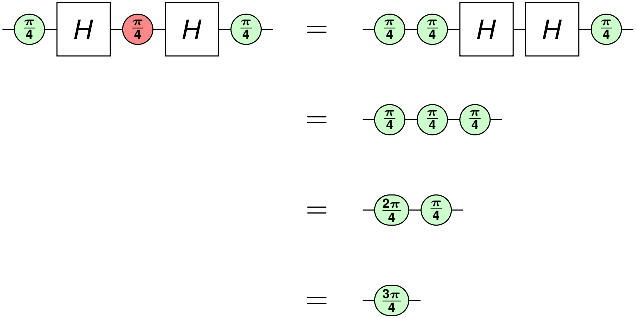

Single Quantum Gates

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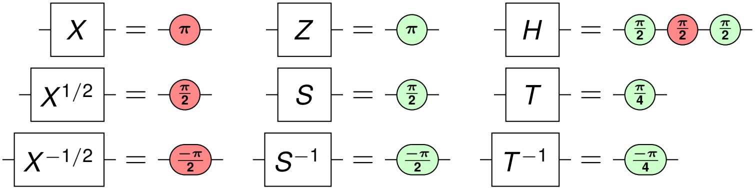
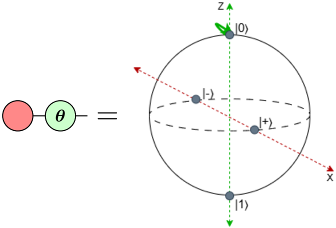
We also give special gate names to commonly used rotations:

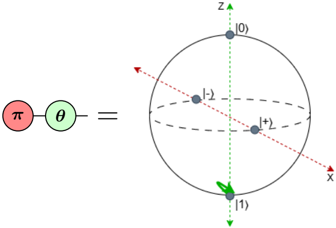


Some Remarks on Global Phase

Rotating the Poles

We can think of $|0\rangle$ and $|1\rangle$ as the north and south poles of the Bloch sphere. If we rotate the Bloch sphere along the Z-axis, then neither pole should move.





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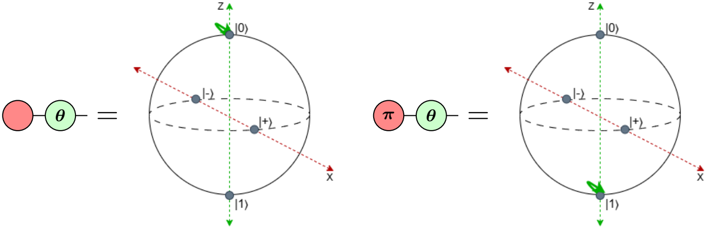
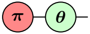
We can think of $|0\rangle$ and $|1\rangle$ as the north and south poles of the Bloch sphere. If we rotate the Bloch sphere along the Z-axis, then neither pole should move.



If we were not using the ZX-calculus, then some of the other math tools might tell us that  actually isn't $|1\rangle$. However, many experiments have shown that this change is *undetectable*.

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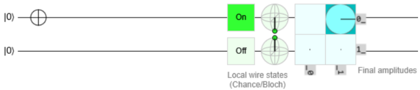

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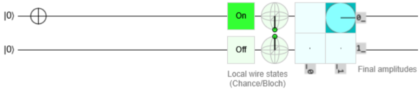
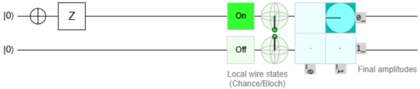


If we apply a Z-rotation to the qubit in state $|1\rangle$, then the amplitude will seemingly change, as a result of global phase!



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