

# From Bits to Qubits: A Beginner's Journey into Quantum Computing



**K.C. Kong**  
**(공경철)**  
University of Kansas



금성고등학교  
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# Plan

- What is a quantum computer?
- Qubit touchdown game
- Quantum bits
- Why quantum computing?
- \$ vs tiger
- Quantum optimization
- Many schools and internship opportunities for graduate, undergraduate, high school students and teachers



# About me

- GS High school graduate (class of 1993)
- Physics major at Pusan National University
- PhD in Theoretical Particle Physics (University of Florida), working on new physics models (extra dimensions, supersymmetry, dark matter etc)
- Research Associate at Fermi National Accelerator Laboratory and Stanford Linear Accelerator Laboratory.
- Currently a faculty at University of Kansas
- Works on MC simulation and data analysis
- Use quantum field theory (advanced quantum mechanics) to understand how the universe works
- [Machine learning and quantum algorithms and their applications](#)
- Teaching quantum algorithms class since 2022
- Mentor students (for quantum machine learning projects) via google summer of codes program
- Not an experimentalist

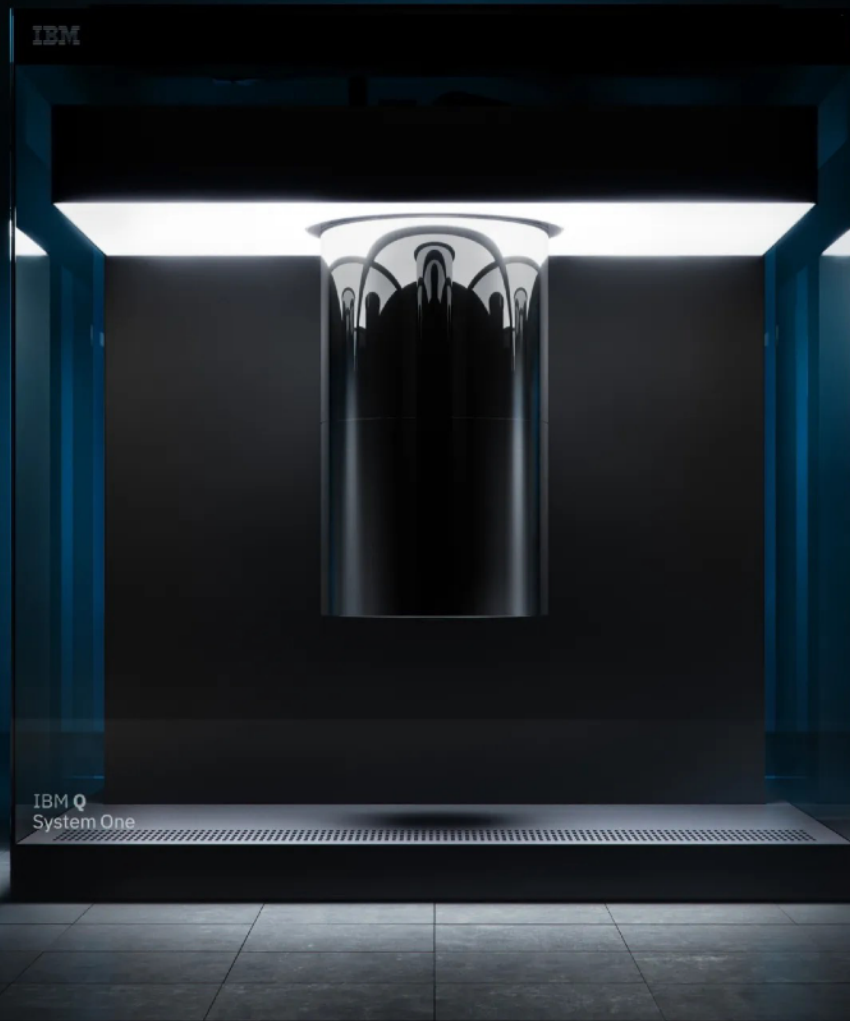
# What is a quantum computer?

- A quantum computer is a new kind of computer that's based on the laws of **quantum physics**.
- It can do **certain** things faster than normal computers because it follows a different set of rules.

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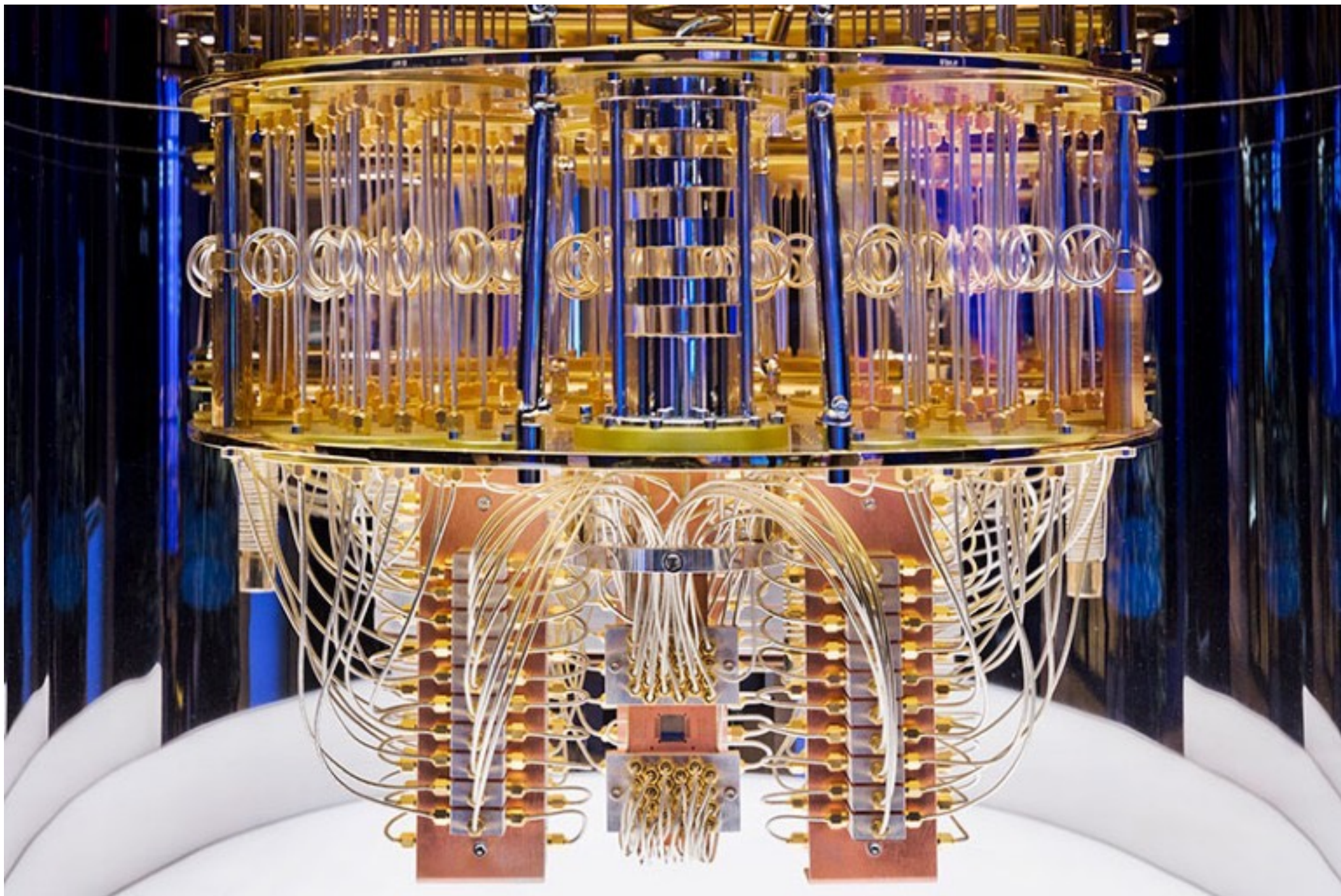




Eagle 127 qubit  
IBM Quantum computer  
Tens of million dollars  
(depending on service contract)







- 01  
Access plans
- 02  
Compare features
- 03  
Technical services
- 04  
Startup Program
- 05  
Case studies

For getting started

## Open Plan

Access quantum computers for up to 10 minutes of runtime per month.

Free

Sign up

View features

For small-scale work

## Pay As You Go Plan

Pay for the quantum computer access you use. Billed per second of usage.

Starts at \$96 USD / minute

Sign up

View features

For project-based work

## Flex Plan

Pre-purchase time for projects that require execution flexibility or bursts of sustained usage.

Starts at \$72 USD / minute

Contact us

View features

For work at scale

## Premium Plan

Subscribe for large-scale capacity with Quantum Allocation Units (QAUs). Use up to 1600 minutes per QAU every 28 days.

Starts at \$48 USD / minute

Contact us

View features

For unparalleled access

## Dedicated Service

Access to a dedicated on-prem quantum system that is serviced and maintained by IBM Quantum.

Price requires quote

Contact us

View features





# What is a quantum computer?

- A quantum computer is a new kind of computer that's based on the laws of **quantum physics**.
- It can do **certain** things faster than normal computers because it follows a different set of rules.
- **Quantum computers are not expected to replace traditional computers for everyday use.** Quantum computers excel at specific types of calculations that are intractable for classical computers, but they are not a general-purpose replacement. Classical computers will remain essential for most tasks, while quantum computers will be used for specialized applications.

# Quantum Computing: A Soccer Analogy

By Thomas Wong



- If the rules were changed so that players could use their hands, soccer would look very different. In some cases, it would be faster or easier for athletes to use their hands to hold, throw, or catch the ball. In other cases, however, it would still be better to kick the ball. For example, most soccer players can kick the ball across the field faster than they can throw the ball or run with it. So, to get the ball across the field as quickly as possible, it may still be better to use one's feet.
- Analogously, the essence of quantum computing is to change the rules so that a computer can now use its “hands.” That is, the rules of the game are changed from the laws of classical physics to the laws of quantum physics. As a result, a quantum computer can solve some problems faster by using its “hands.” For other problems, using one's “feet” is better, so a quantum computer is no faster for these problems.



# Need transition form classical to quantum:

● 0

● 1

Classical

bits

gates

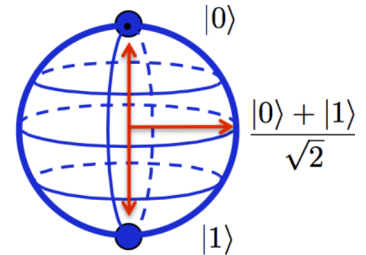
algorithms

Quantum

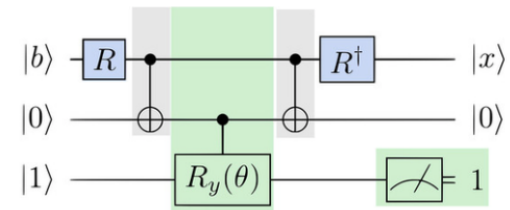
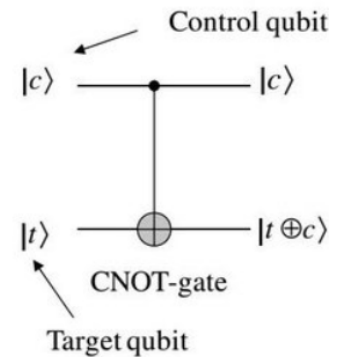
qubits

quantum  
gates

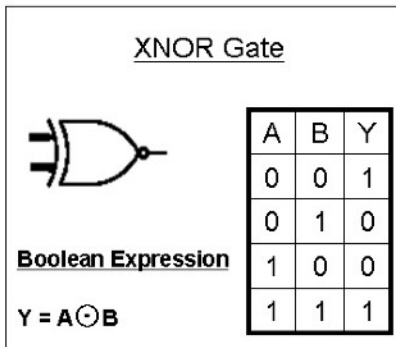
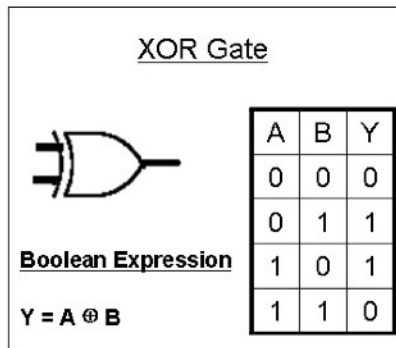
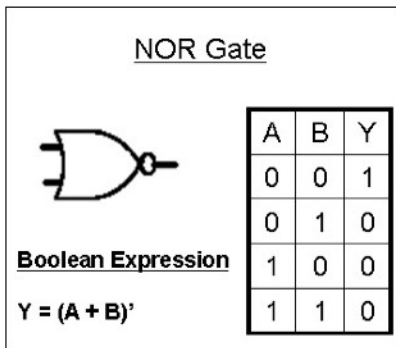
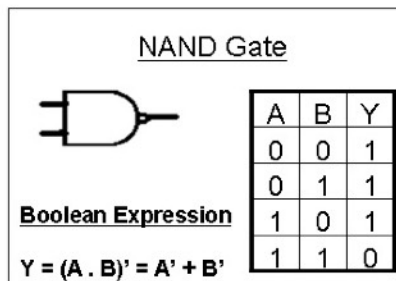
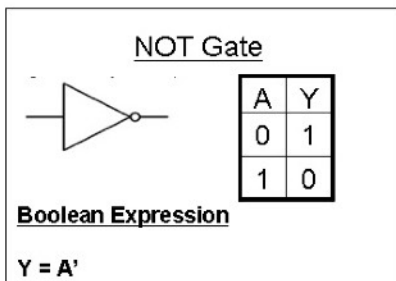
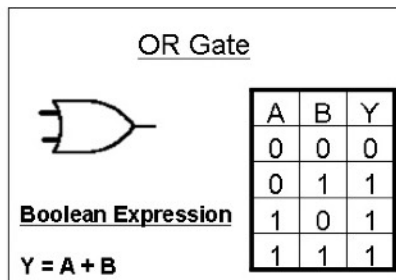
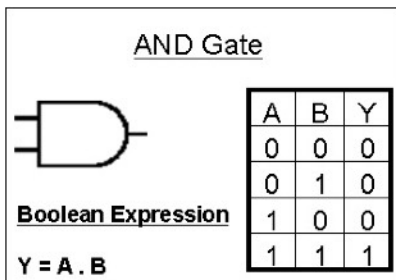
quantum algorithms



**Qubit**



# classical gates



# Quantum gates

[illegible]

# Qubit Touchdown

- A quantum computing board game
  - Released Dec. 2019
- Make your own copy – instructions at [thomaswong.net](https://thomaswong.net)
- Buy a professionally produced copy print-on-demand at [thegamecrafter.com](https://thegamecrafter.com)
- Study involving 107 public high school students in Precalculus, AP Statistics, and/or AP Physics 1
  - Conducted Dec. 2024
  - Submitted Jan. 2025, <https://arxiv.org/abs/2501.10449>

Made by Prof. Tom Wong  
Creighton University

## Improving Student Self-Efficacy in Quantum Computing with the Qubit Touchdown Board Game

Kristina Armbruster,<sup>1</sup> Gintaras Duda,<sup>2</sup> and Thomas G. Wong<sup>2</sup>

<sup>1</sup>Bellevue West High School, 1501 Thurston Ave, Bellevue, Nebraska 68123

<sup>2</sup>Department of Physics, Creighton University, 2500 California Plaza, Omaha, Nebraska 68178



Qubit Touchdown is a two-player, competitive game. The game board is shown in Fig. 2, and the football token or gem is placed on the board to indicate the position of the football. The football can only be at the six positions indicated by yellow circles, which are labeled 0, 1, +, -,  $i$ , and  $-i$ . One player is trying to get the football to the + endzone to score touchdowns, and the other player is trying to get the ball to the - endzone to score touchdowns. They take turns playing cards to move the football along the

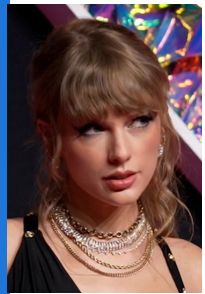
## II. HOW TO PLAY QUBIT TOUCHDOWN

As a high-level overview, Qubit Touchdown is a two player, competitive game. The game board is shown in Fig. 2, and the football token or gem is placed on the board to indicate the position of the football. The football can only be at the six positions indicated by yellow circles, which are labeled 0, 1, +, -,  $i$ , and  $-i$ . One player is trying to get the football to the + endzone to score touchdowns, and the other player is trying to get the ball to the - endzone to score touchdowns. They take turns playing cards to move the football along the

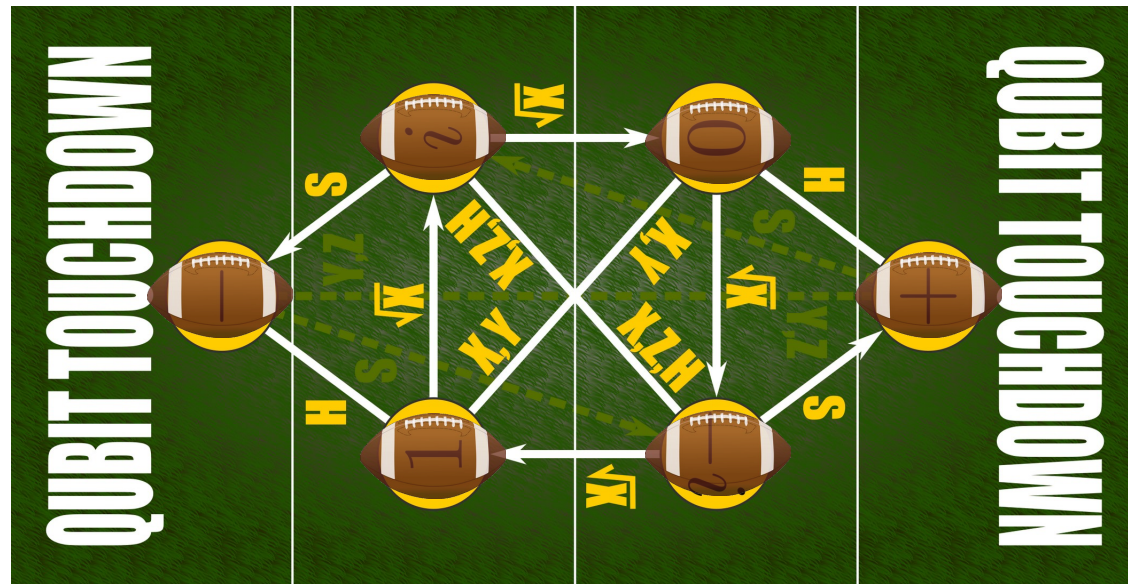
<sup>a</sup>Electronic mail: [kristina.armbruster@bpsnc.net](mailto:kristina.armbruster@bpsnc.net)

<sup>b</sup>Electronic mail: [gkduda@creighton.edu](mailto:gkduda@creighton.edu)

<sup>c</sup>Electronic mail: [thomaswong@creighton.edu](mailto:thomaswong@creighton.edu)



**Taylor**



**Ryan**

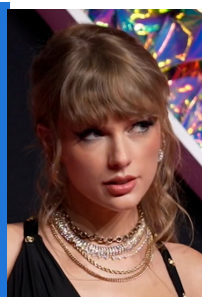


- The football can be in one of six positions: 0, 1, +, -, i, or -i.

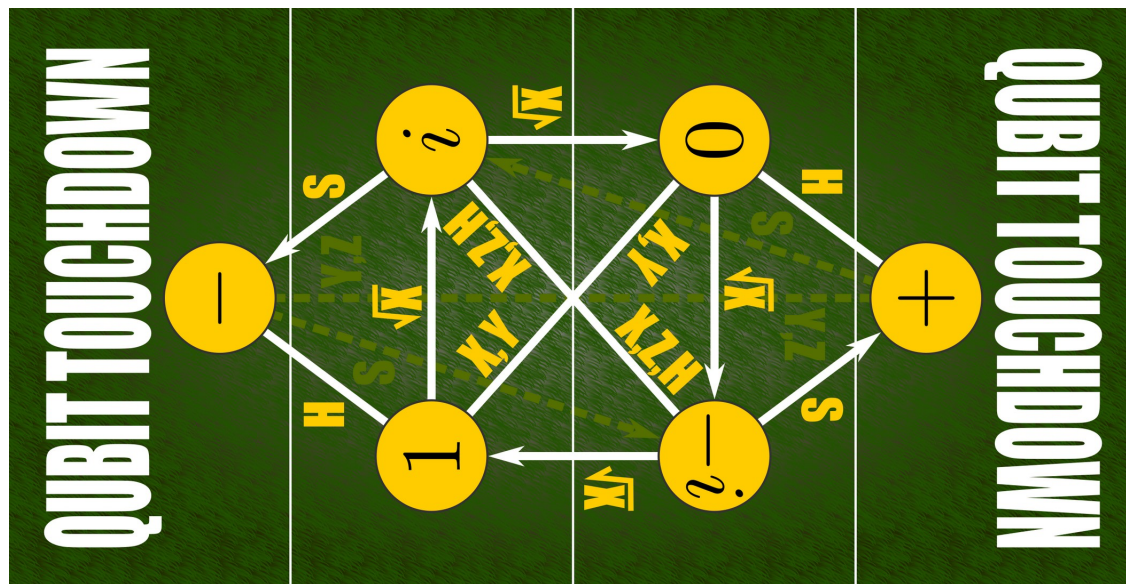




- Taylor is trying to get the ball to the “+” endzone, and Ryan is trying to get the ball to the “−” endzone, to score touchdowns.



**Taylor**



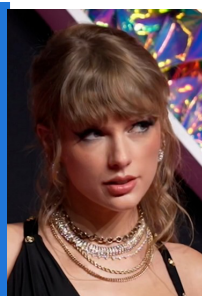
**Ryan**



- They take turns playing cards to move the ball along the lines/arrows.
- Whoever scores the most touchdowns by the time all 52 cards are played wins.

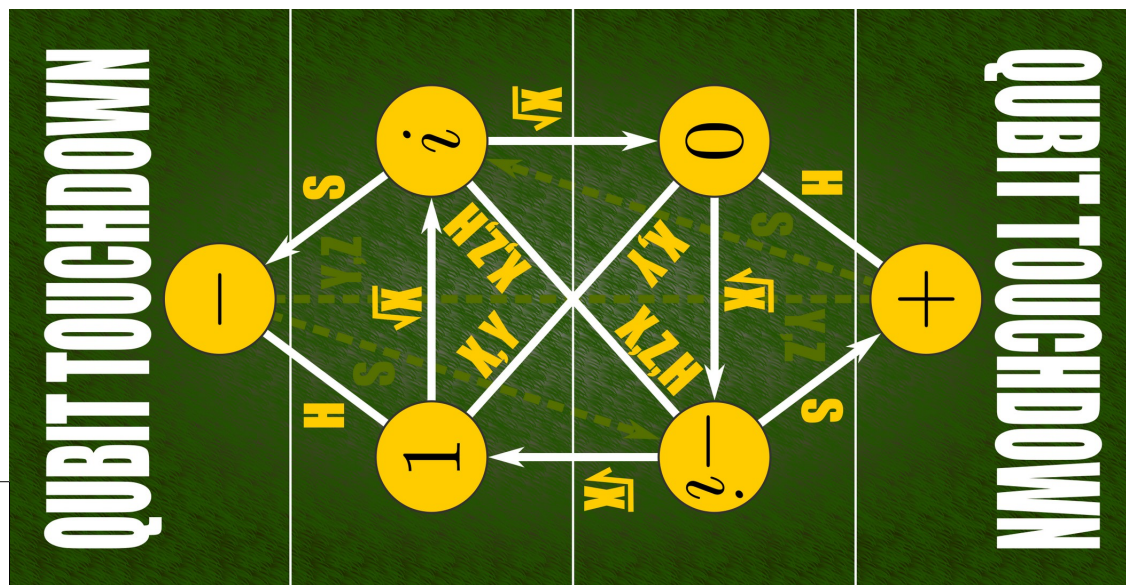
Let's play Qubit touchdown!





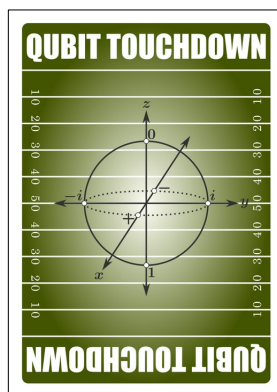
**Taylor**

Touchdowns: 0



Draw Pile

Discard Pile



44 cards

0 cards

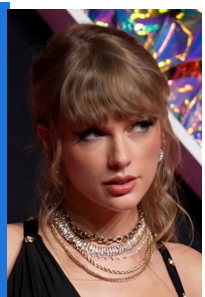
**Ryan**

Touchdowns: 0



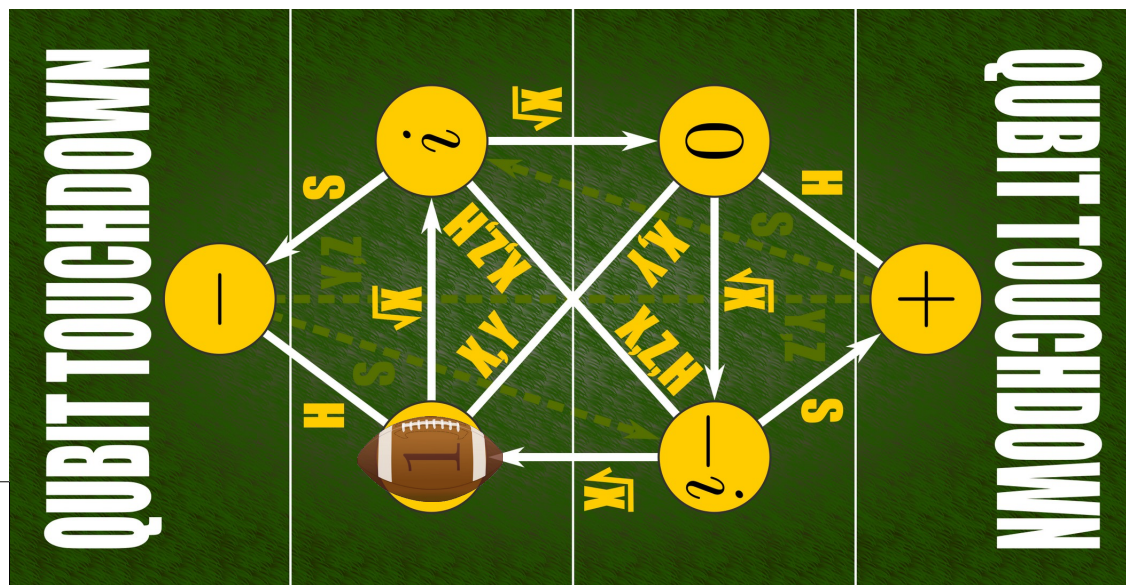
- Shuffle the cards. Deal 4 to each player. Put the rest in the middle as a “draw pile.”





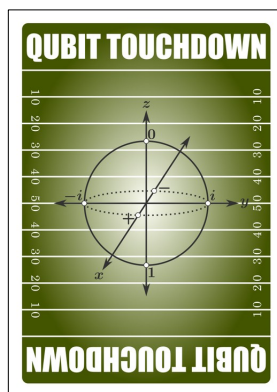
**Taylor**

Touchdowns: 0



Draw Pile

Discard Pile



44 cards

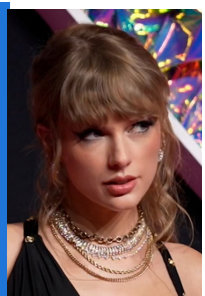
0 cards

**Ryan**

Touchdowns: 0

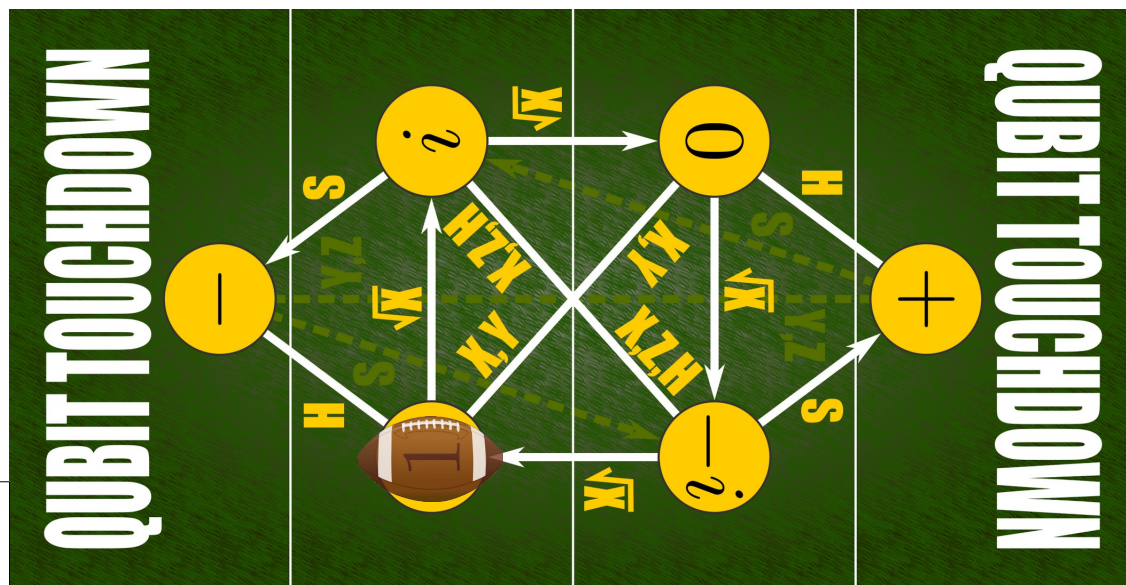


- Taylor “kicks off” by rolling the binary die and placing the football at the result.



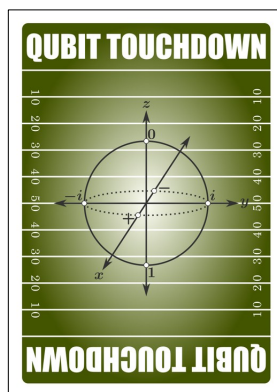
**Taylor**

Touchdowns: 0



Draw Pile

Discard Pile



44 cards



**Ryan**

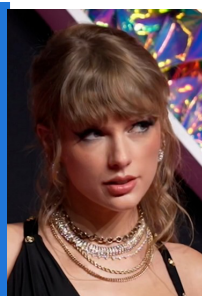
Touchdowns: 0



0 cards

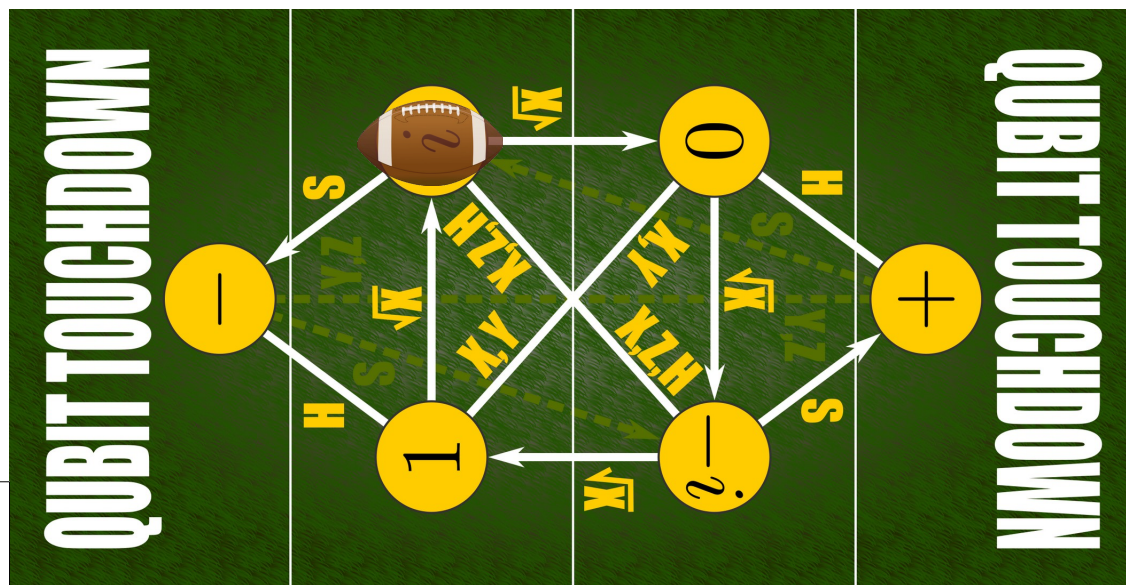
- **Ryan's** turn. He wants to get the ball to “-” to score, but he doesn't have an “H.”





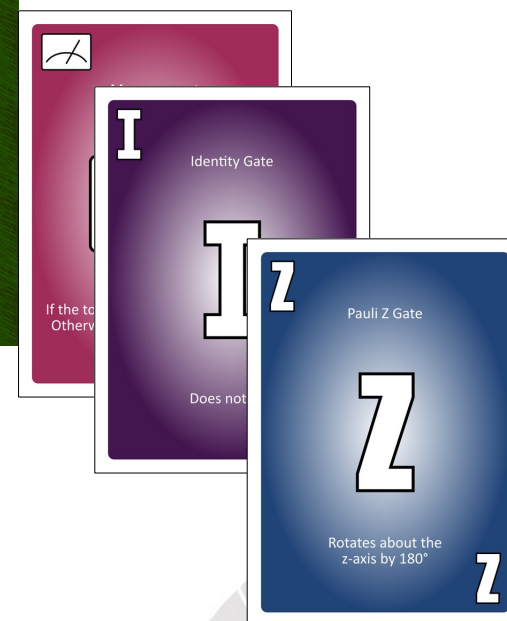
**Taylor**

Touchdowns: 0

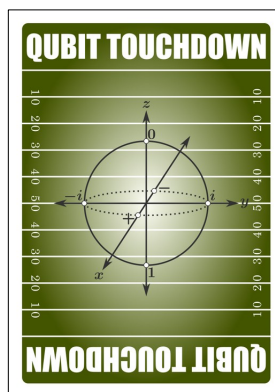


**Ryan**

Touchdowns: 0

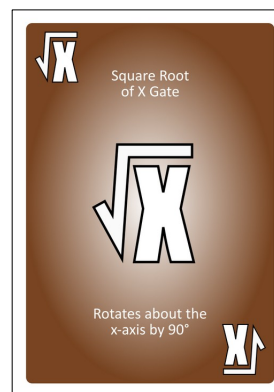


Draw Pile



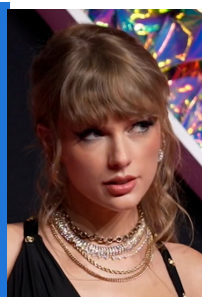
44 cards

Discard Pile



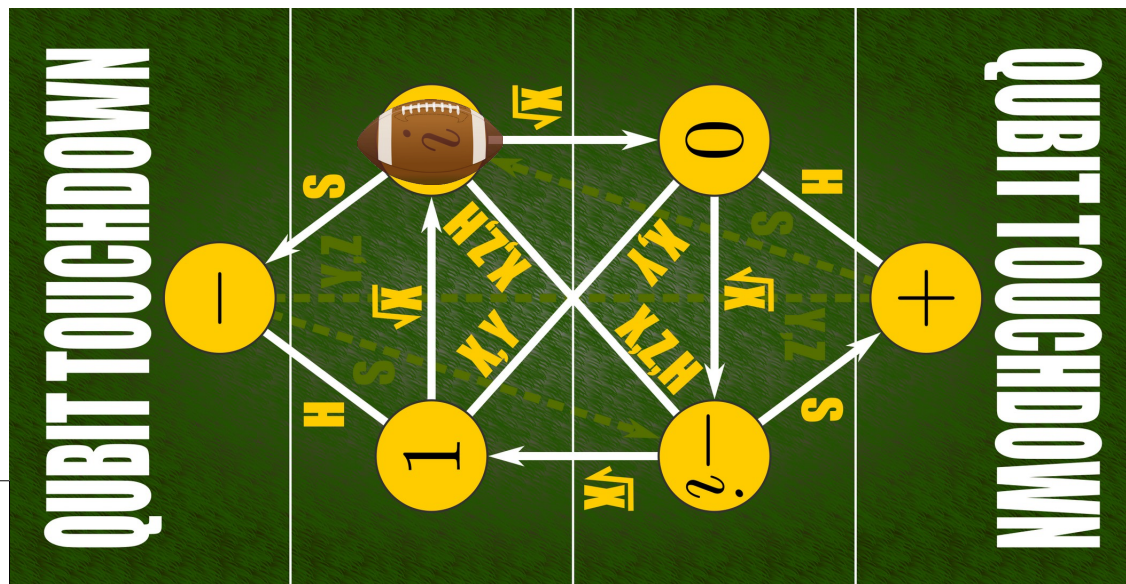
1 card

- He plays " $\sqrt{X}$ " and moves the ball to "i."

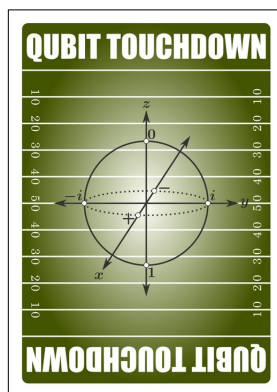


**Taylor**

Touchdowns: 0

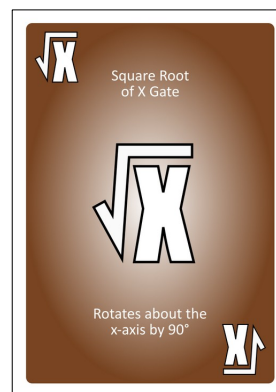


Draw Pile



43 cards

Discard Pile



1 card

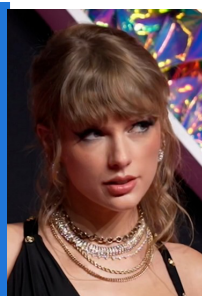
**Ryan**

Touchdowns: 0



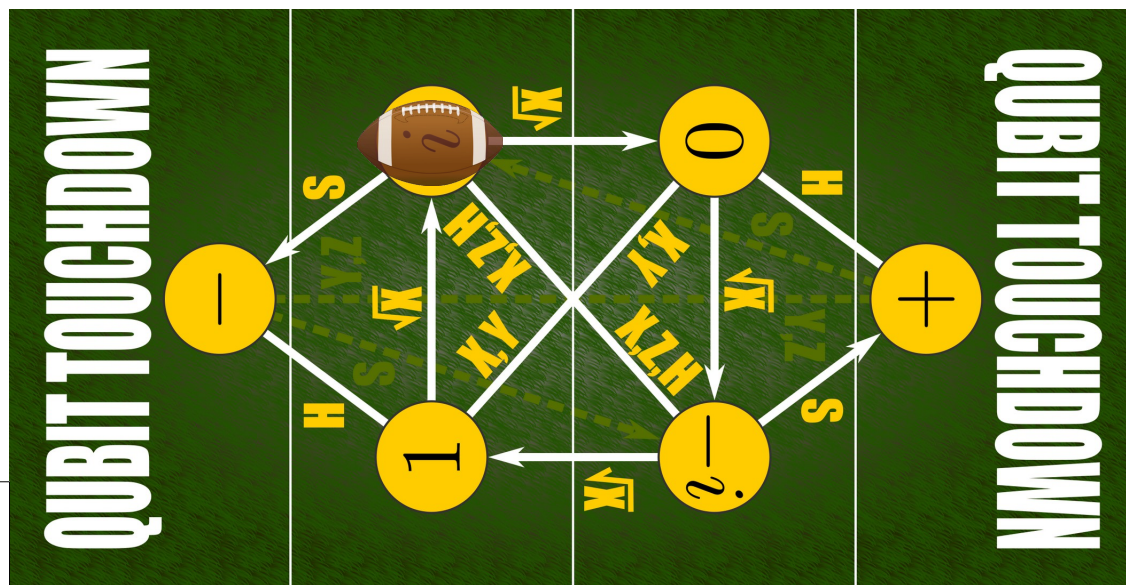
- He draws a new card.





**Taylor**

Touchdowns: 0

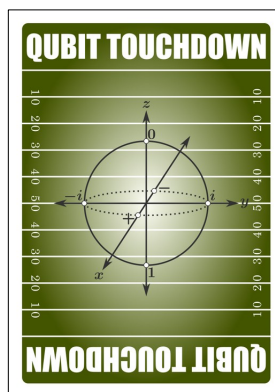


**Ryan**

Touchdowns: 0

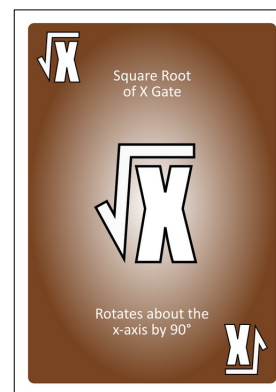


Draw Pile



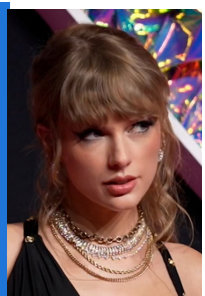
43 cards

Discard Pile



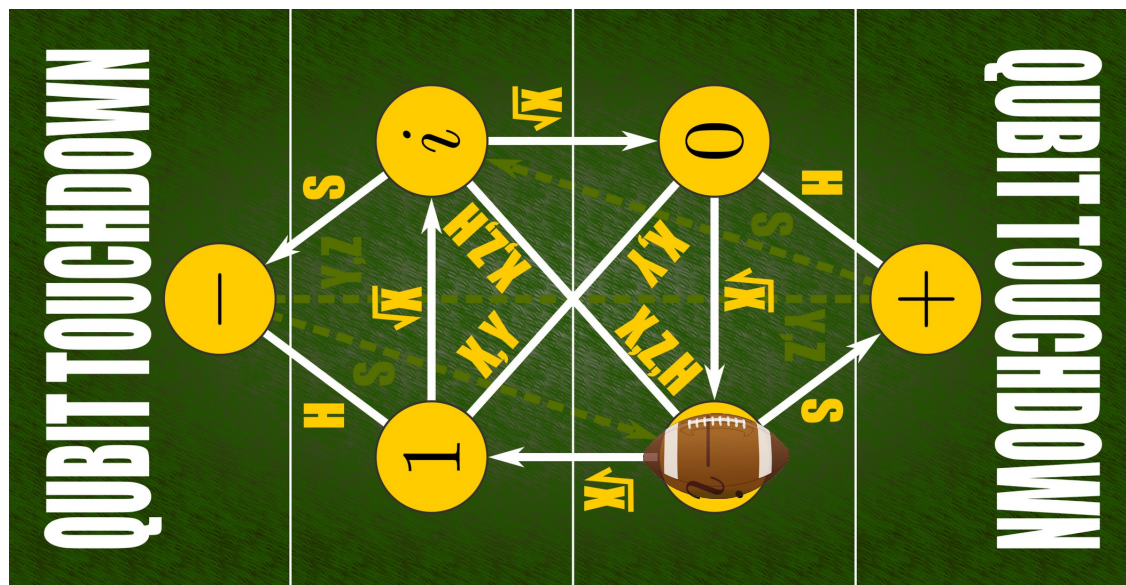
1 card

- **Taylor's** turn. She wants to move the ball towards "+."



**Taylor**

Touchdowns: 0



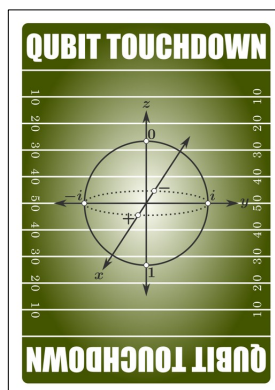
**Ryan**

Touchdowns: 0

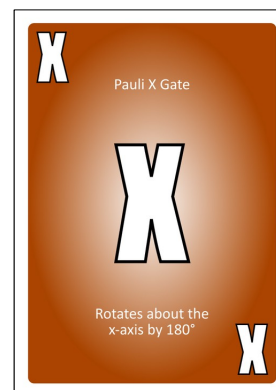


Draw Pile

Discard Pile



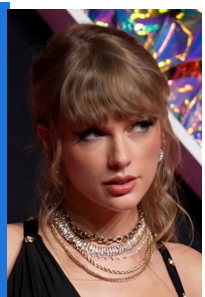
43 cards



2 cards

- She plays “X” and moves the ball to “-i.”



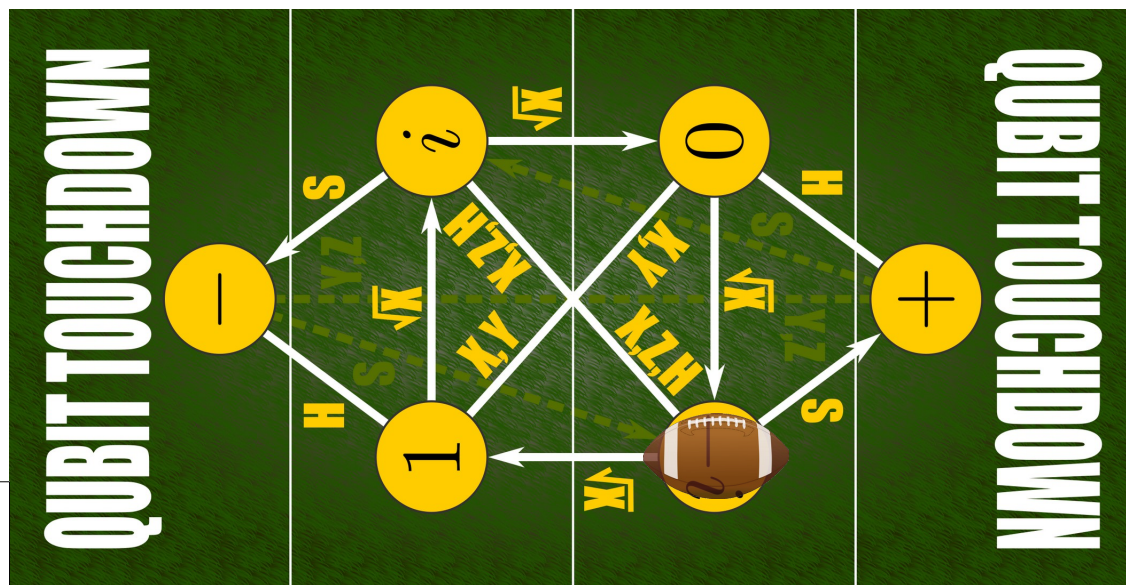


**Taylor**

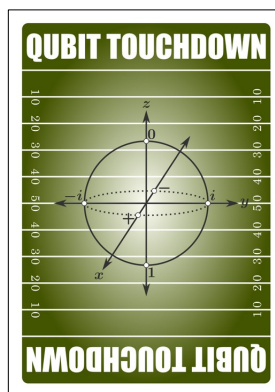
Touchdowns: 0



- She draws a new card.

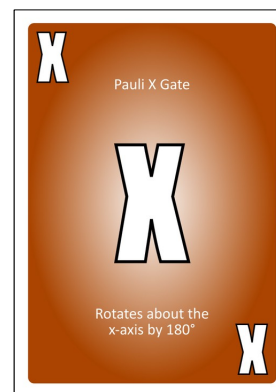


Draw Pile



42 cards

Discard Pile



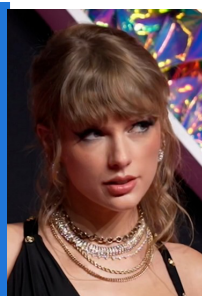
2 cards

**Ryan**

Touchdowns: 0

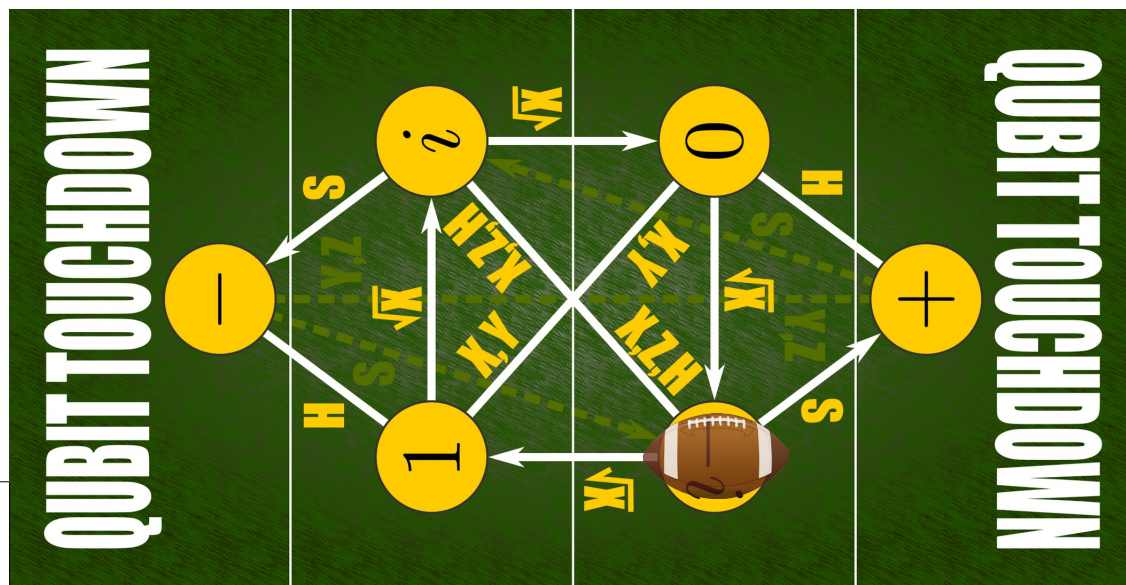




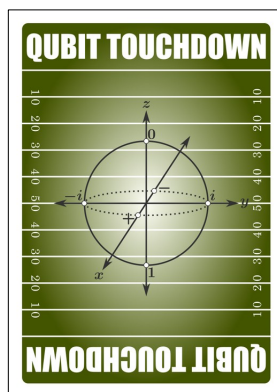


**Taylor**

Touchdowns: 0

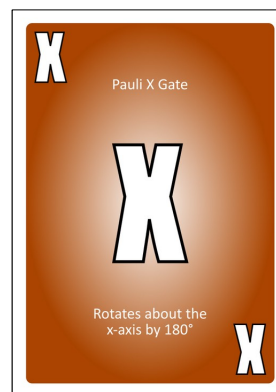


Draw Pile



42 cards

Discard Pile



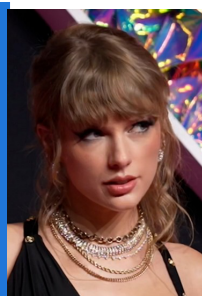
2 cards

**Ryan**

Touchdowns: 0



- **Ryan's** turn.



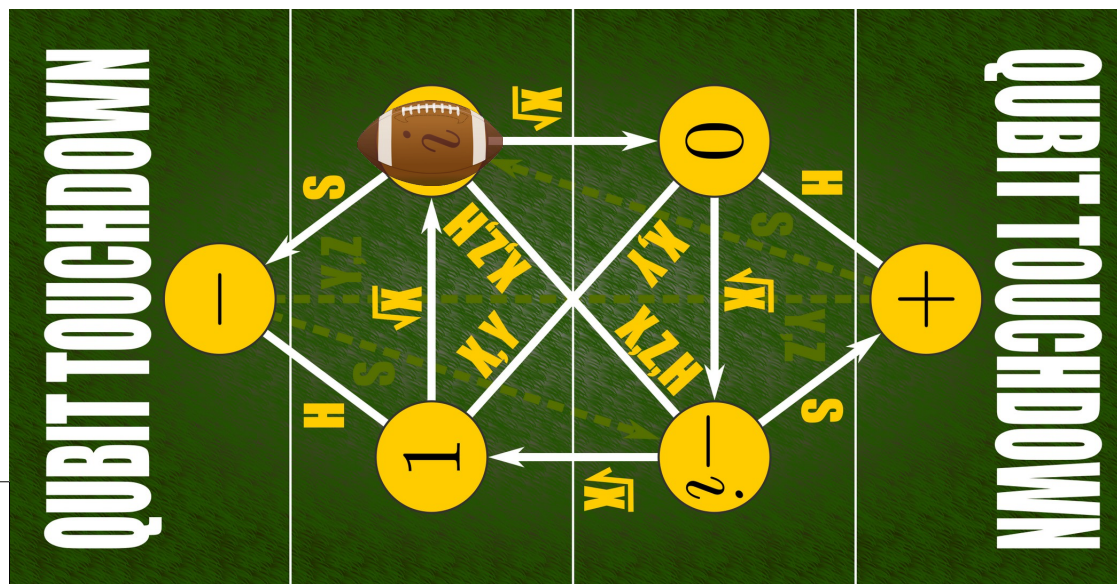
**Taylor**

Touchdowns: 0

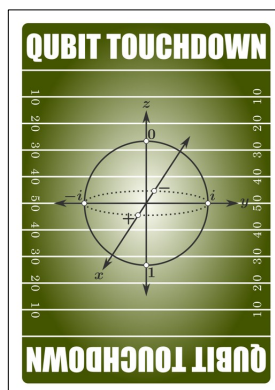


**Ryan**

Touchdowns: 0

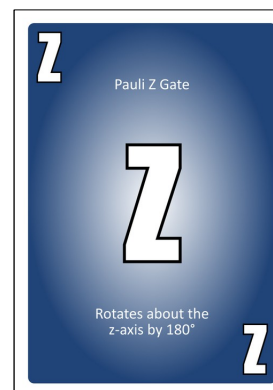


Draw Pile



42 cards

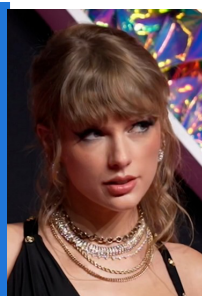
Discard Pile



3 cards

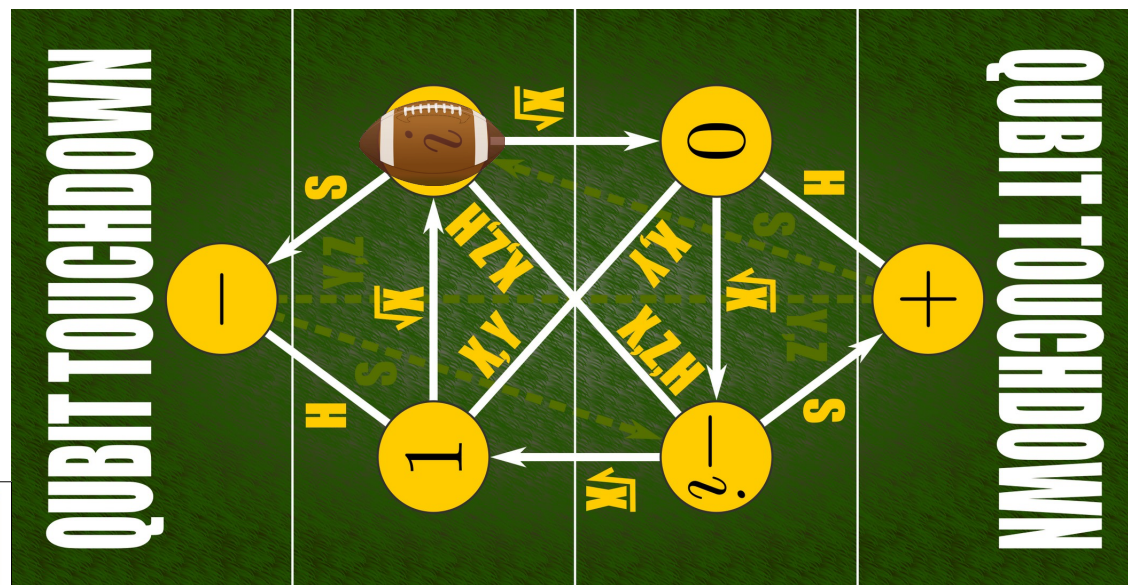
- He plays “Z” and moves the ball to “i.”



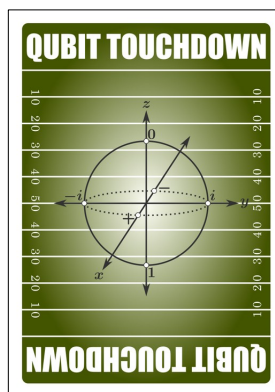


**Taylor**

Touchdowns: 0

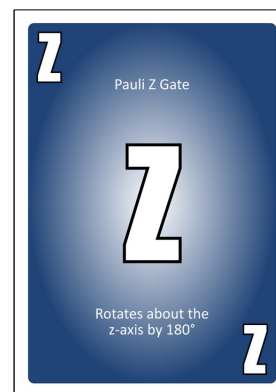


Draw Pile



41 cards

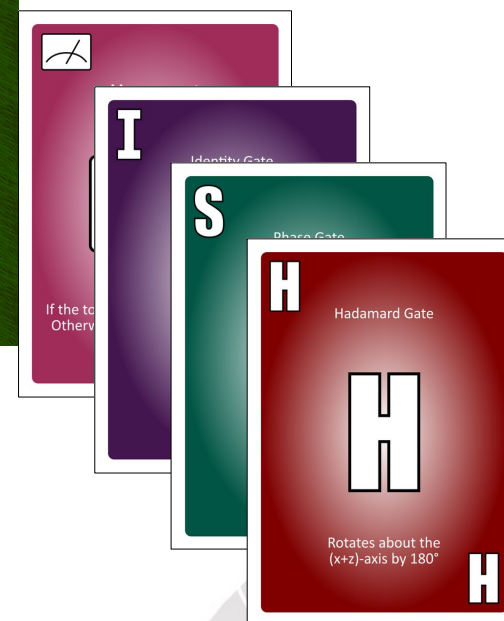
Discard Pile



3 cards

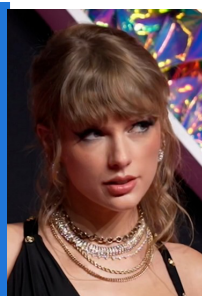
**Ryan**

Touchdowns: 0



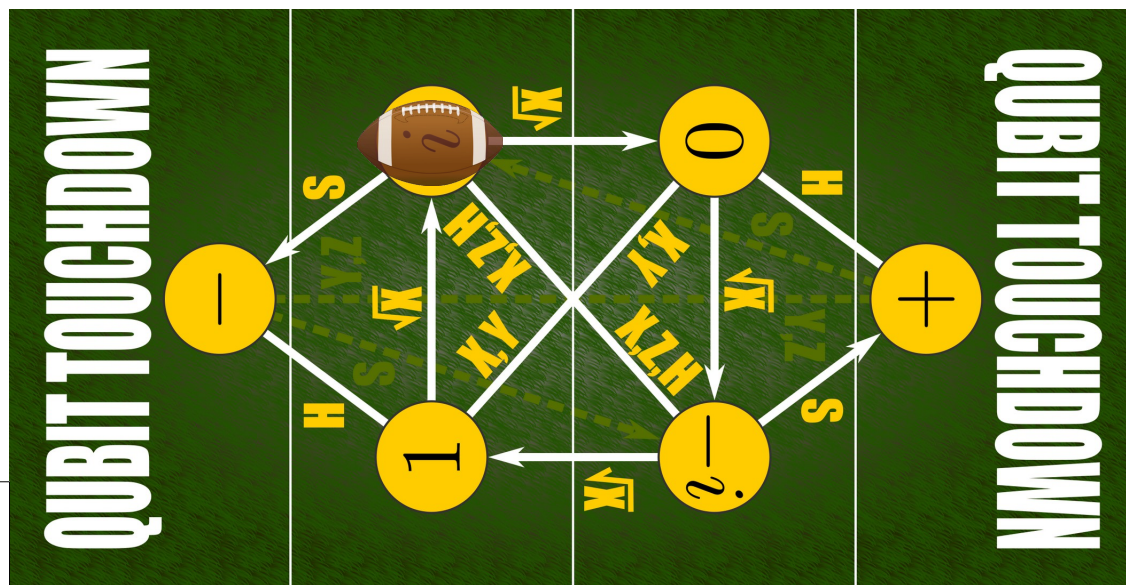
- He draws another card.



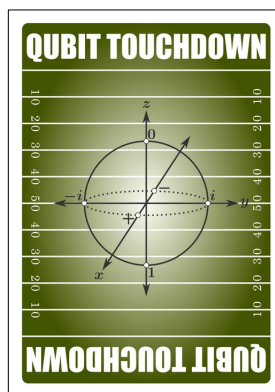


**Taylor**

Touchdowns: 0

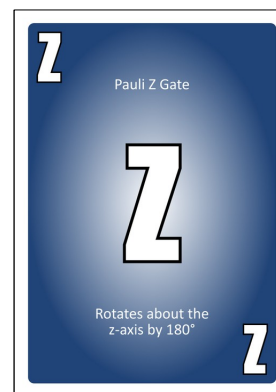


Draw Pile



41 cards

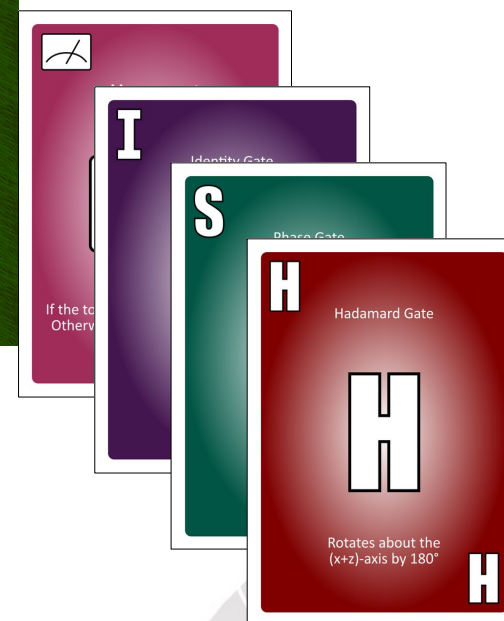
Discard Pile



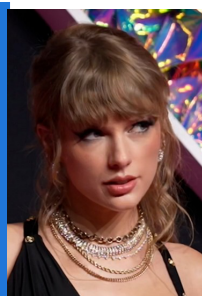
3 cards

**Ryan**

Touchdowns: 0

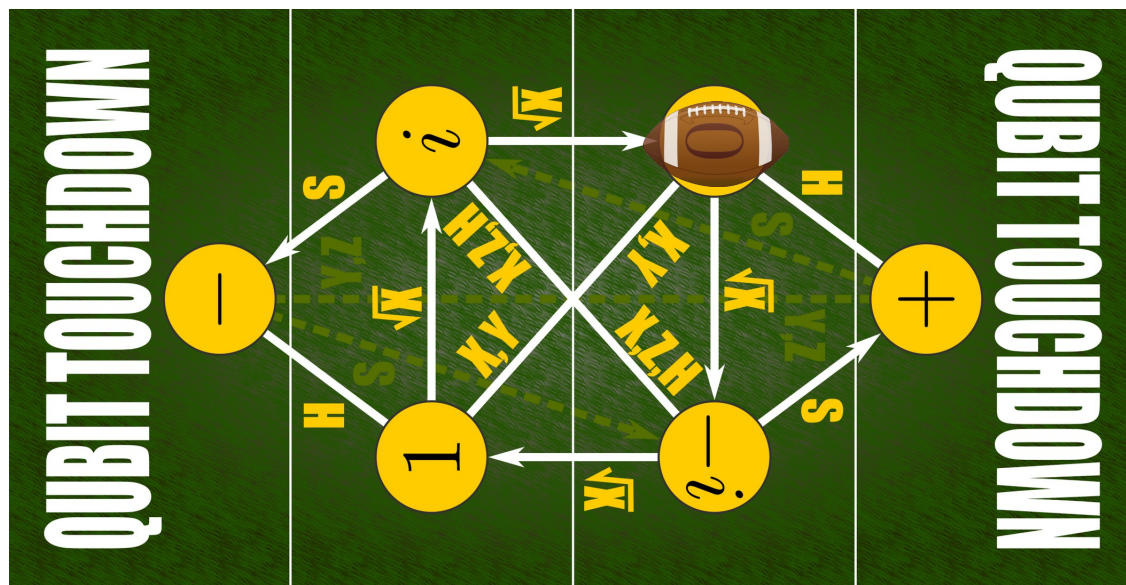


- **Taylor's** turn.



**Taylor**

Touchdowns: 0



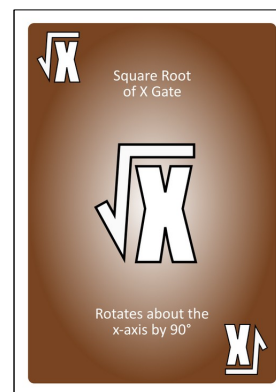
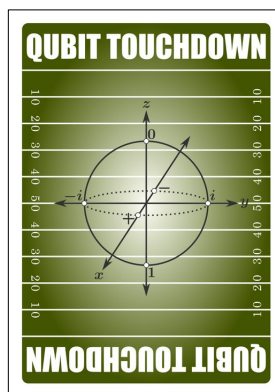
**Ryan**

Touchdowns: 0



Draw Pile

Discard Pile

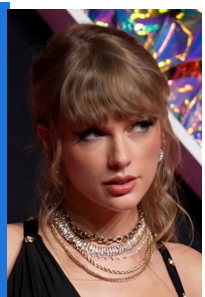


41 cards

4 cards

- She plays “ $\sqrt{X}$ ” and moves the ball to “0.”



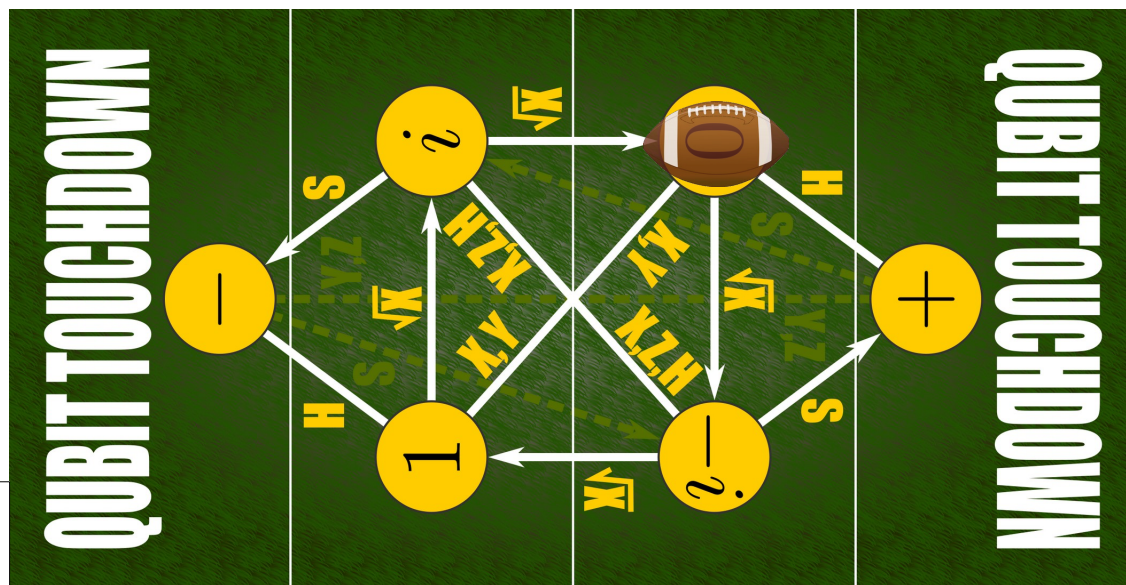


**Taylor**

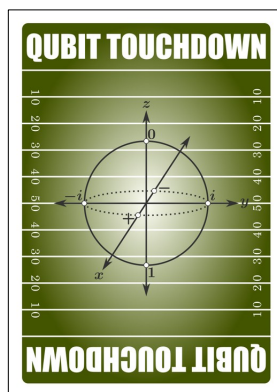
Touchdowns: 0



- She draws another card.

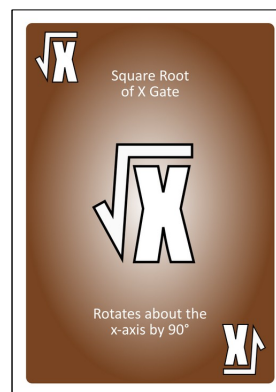


Draw Pile



40 cards

Discard Pile



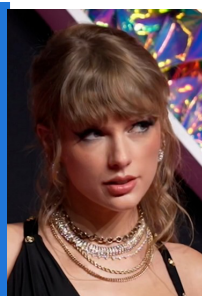
4 cards

**Ryan**

Touchdowns: 0

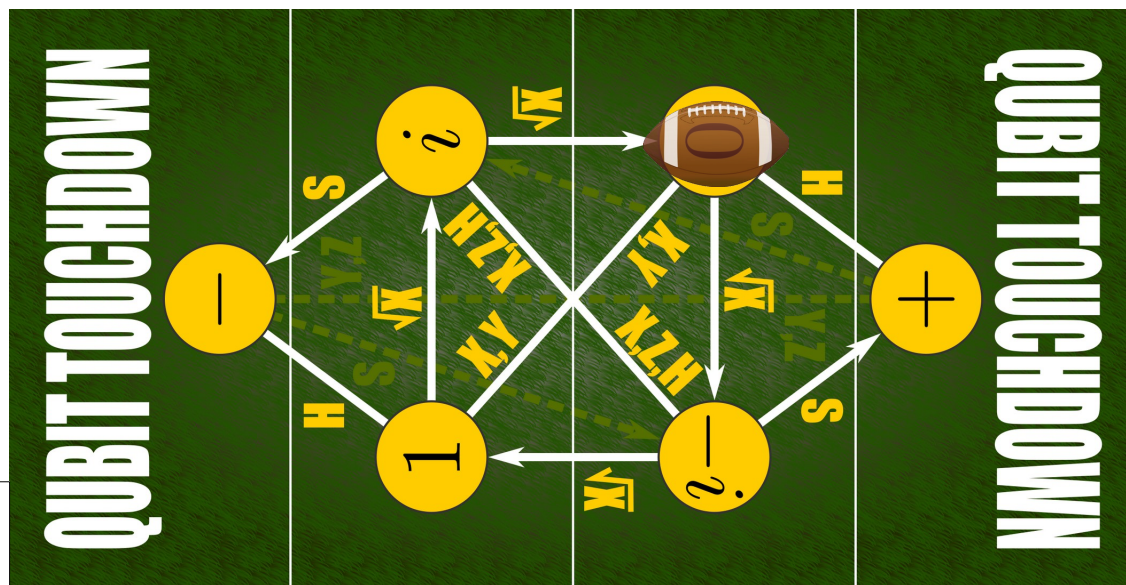




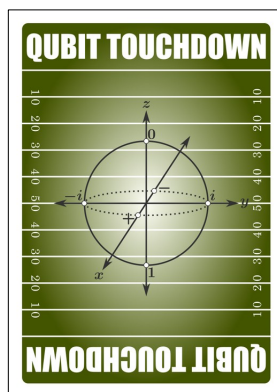


**Taylor**

Touchdowns: 0

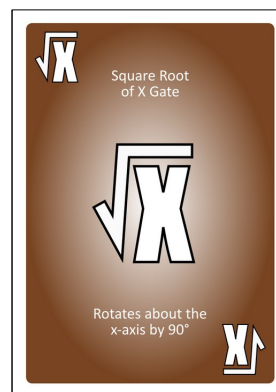


Draw Pile



40 cards

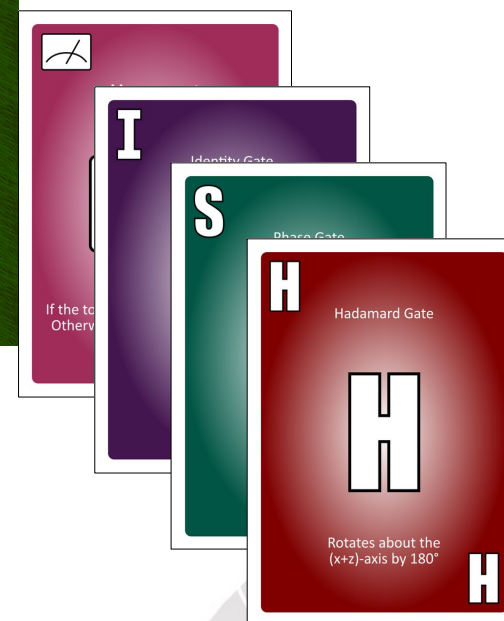
Discard Pile



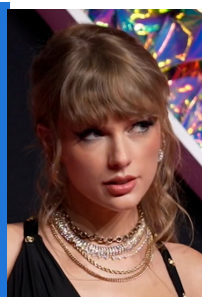
4 cards

**Ryan**

Touchdowns: 0

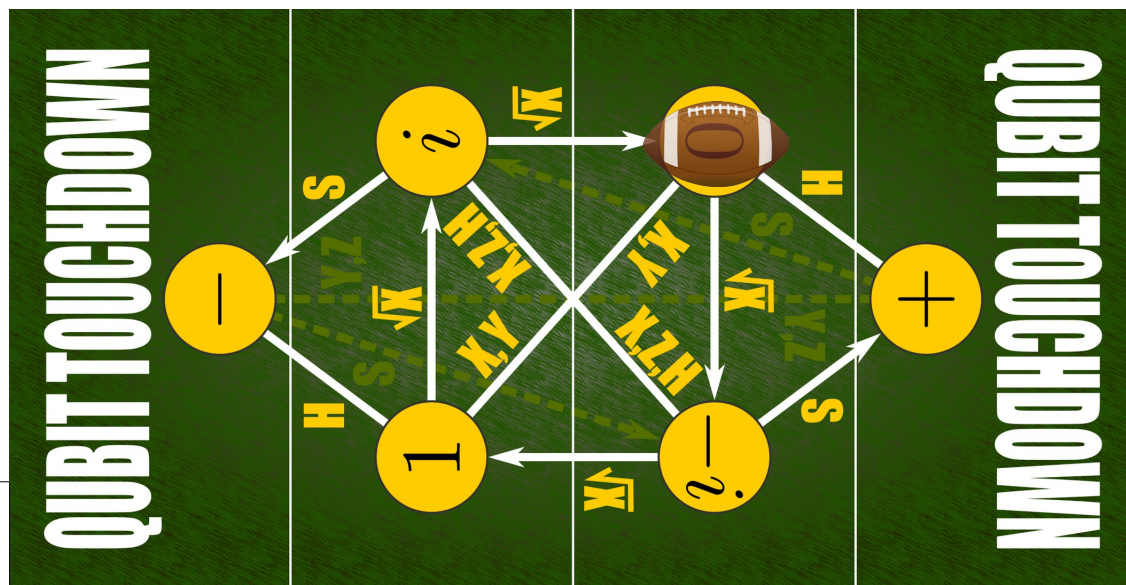


- **Ryan's** turn.



**Taylor**

Touchdowns: 0

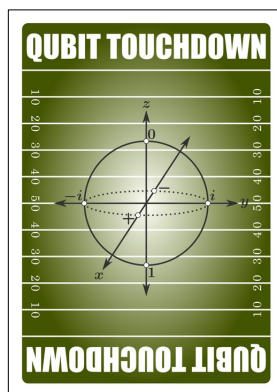


**Ryan**

Touchdowns: 0

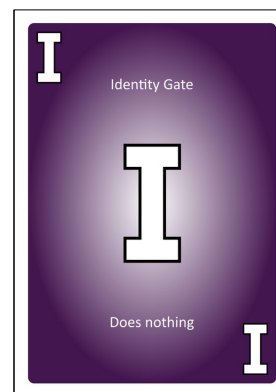


Draw Pile



40 cards

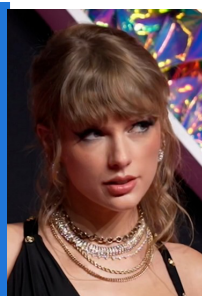
Discard Pile



5 cards

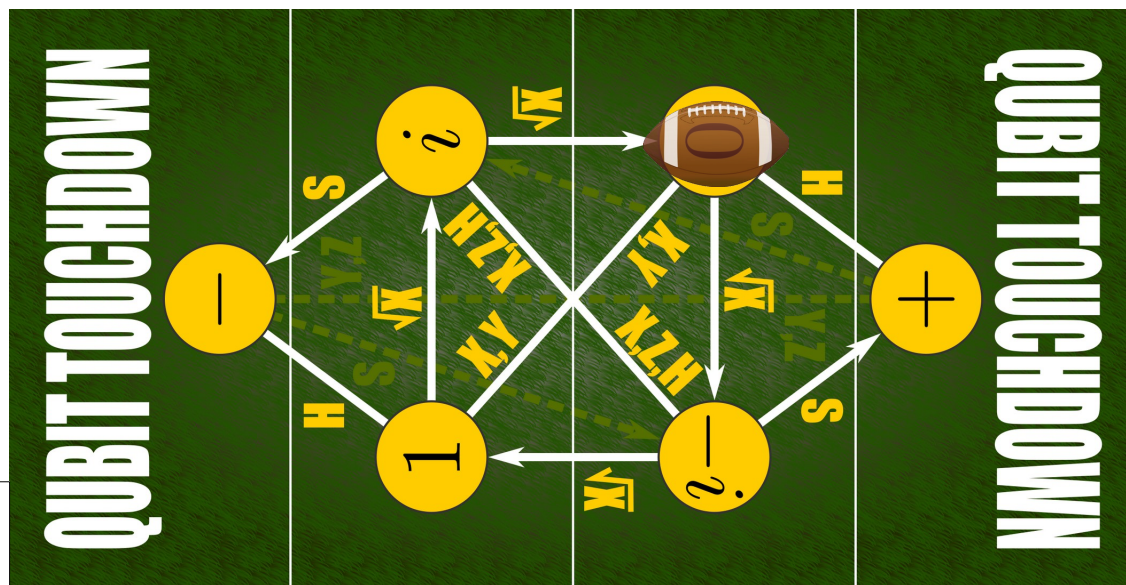
- He plays "I" and leaves the ball unmoved.



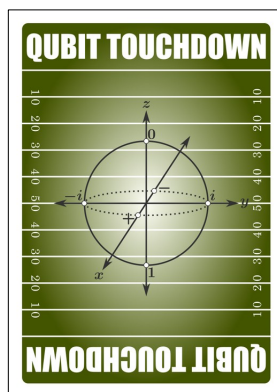


**Taylor**

Touchdowns: 0

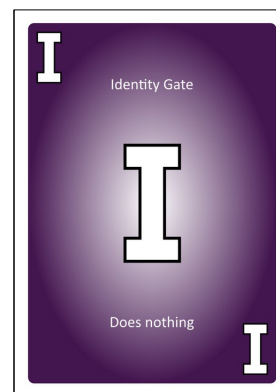


Draw Pile



39 cards

Discard Pile



5 cards

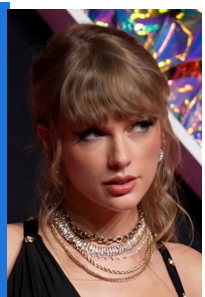
**Ryan**

Touchdowns: 0



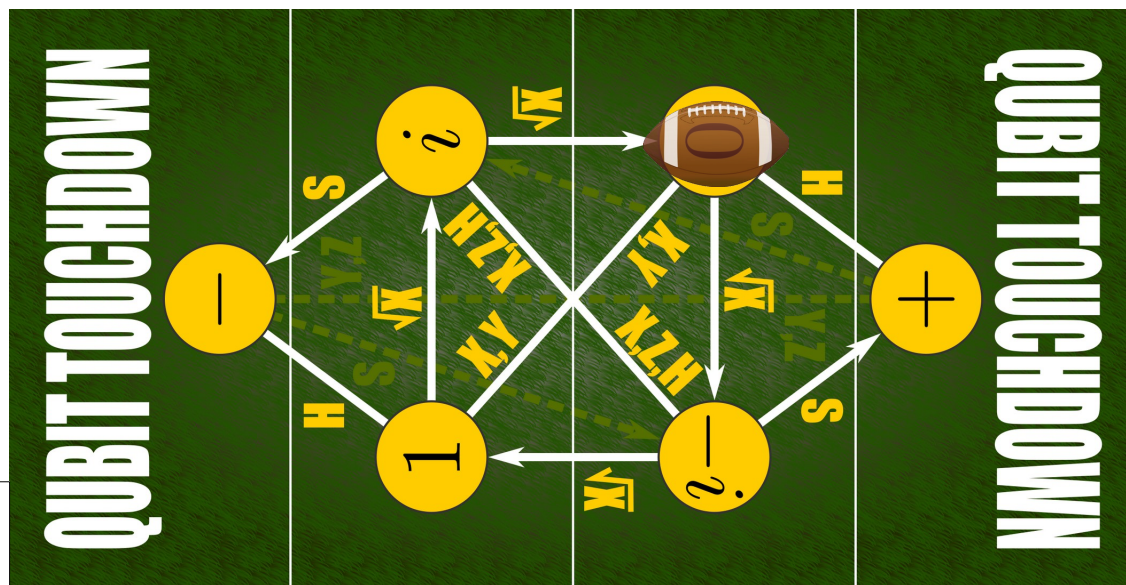
- He draws another card.





**Taylor**

Touchdowns: 0

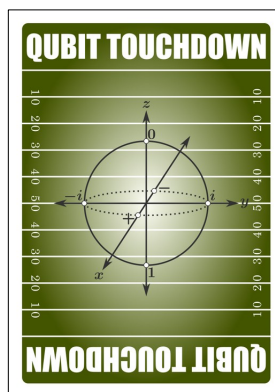


**Ryan**

Touchdowns: 0

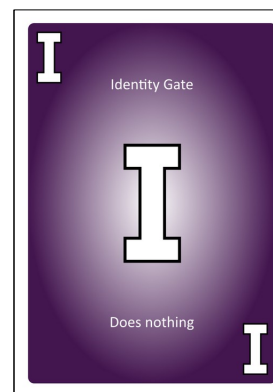


Draw Pile



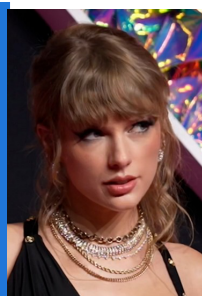
39 cards

Discard Pile



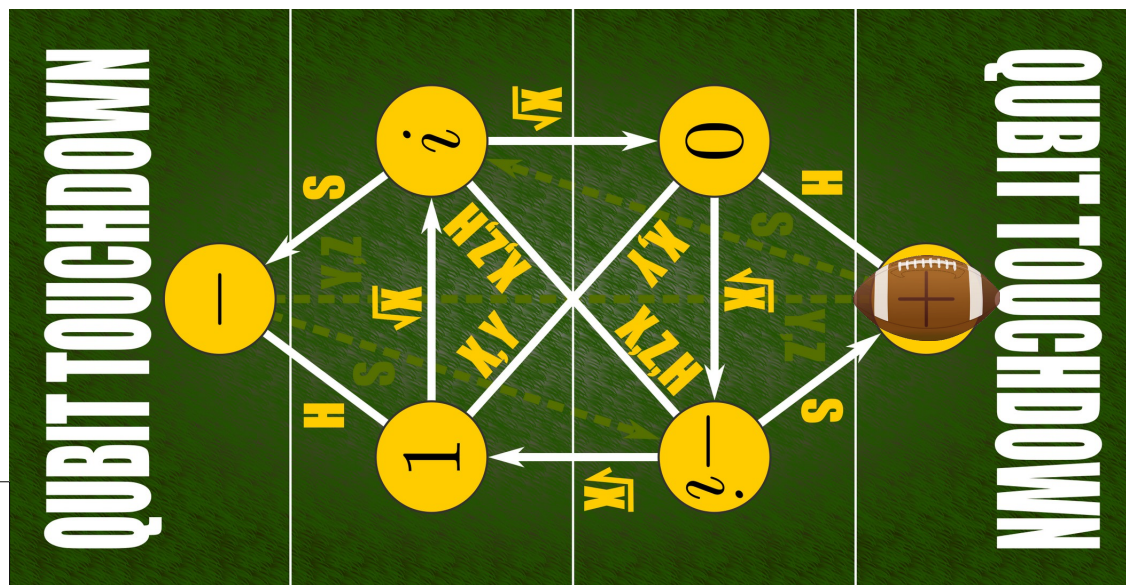
5 cards

- **Taylor's** turn.



**Taylor**

Touchdowns: 1

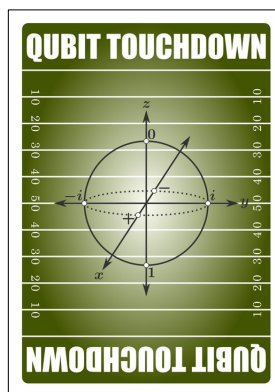


**Ryan**

Touchdowns: 0

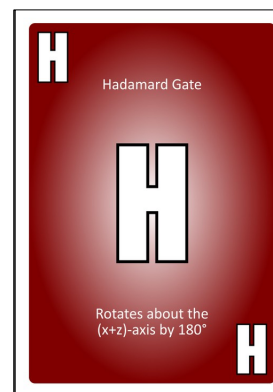


Draw Pile



39 cards

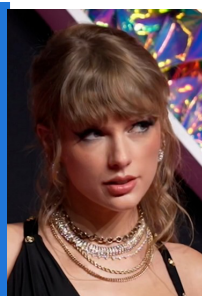
Discard Pile



6 cards

- She plays “H” and moves the ball to “+.” Touchdown!



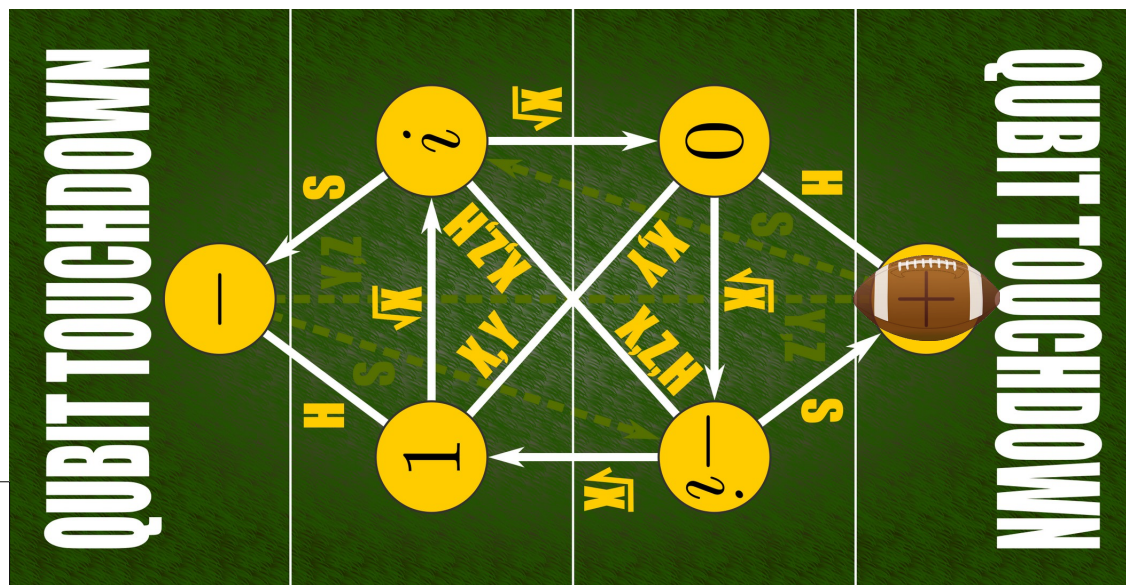


**Taylor**

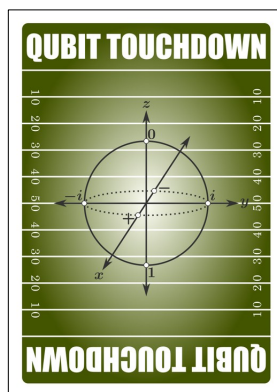
Touchdowns: 1



- She draws another card.

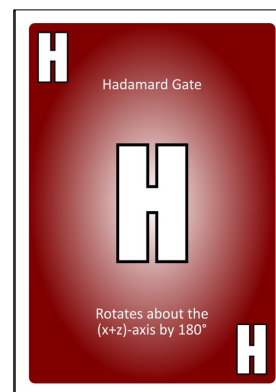


Draw Pile



38 cards

Discard Pile



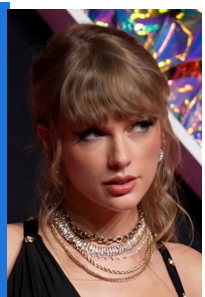
6 cards

**Ryan**

Touchdowns: 0

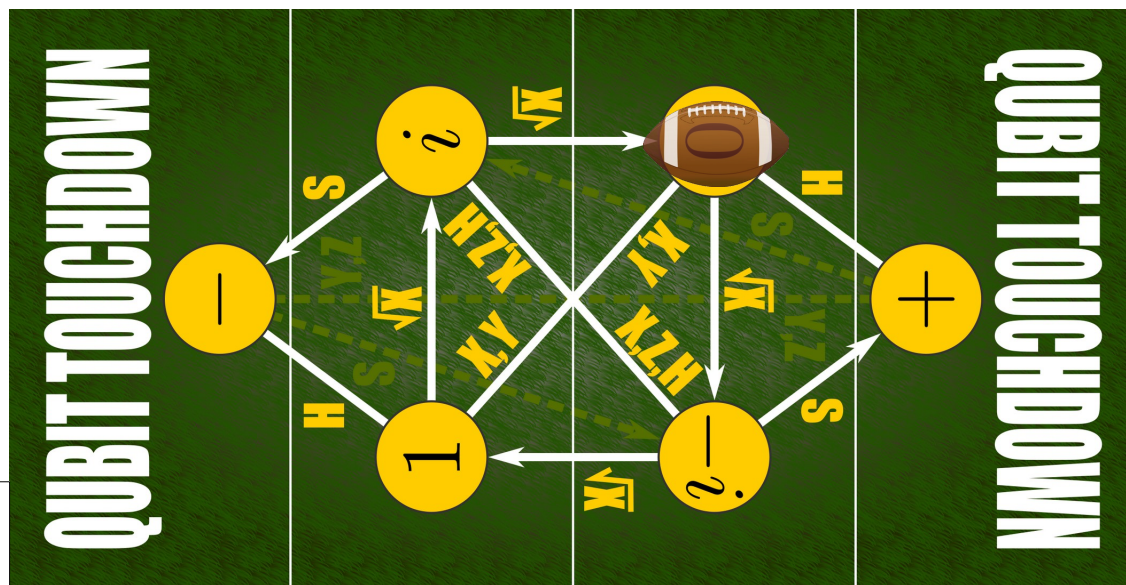






**Taylor**

Touchdowns: 1

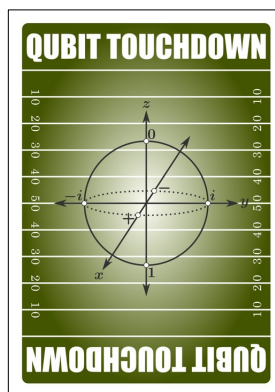


**Ryan**

Touchdowns: 0

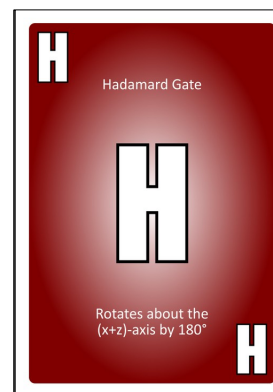


Draw Pile



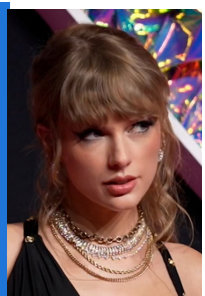
38 cards

Discard Pile



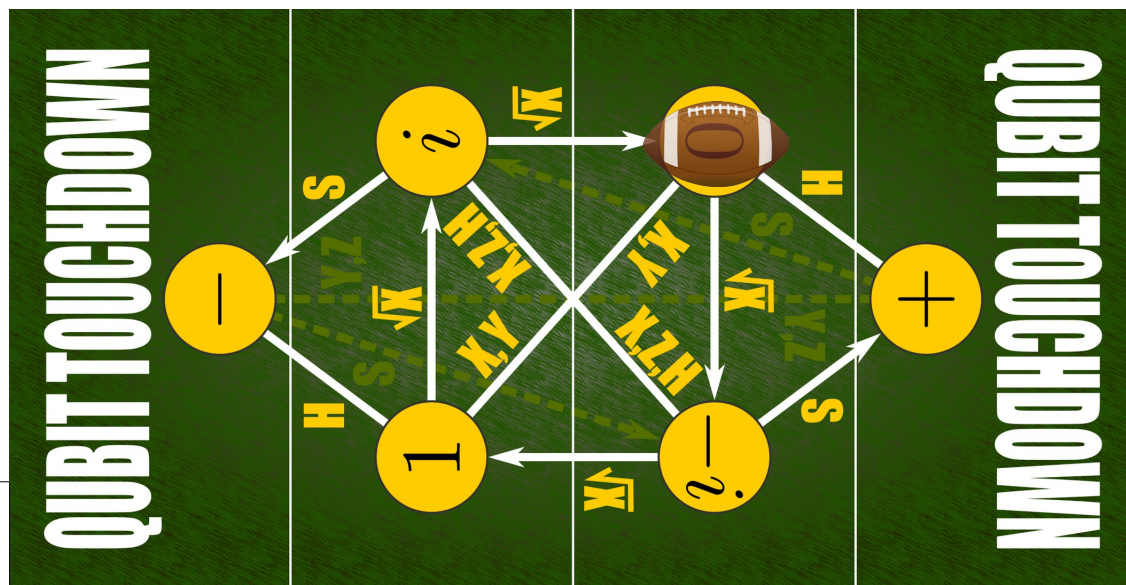
6 cards

- Since she scored a touchdown, she kicks off by rolling the binary die.



**Taylor**

Touchdowns: 1

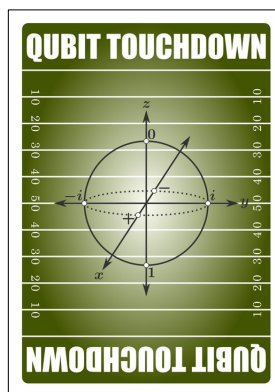


**Ryan**

Touchdowns: 0

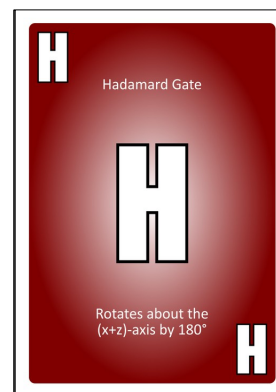


Draw Pile



38 cards

Discard Pile



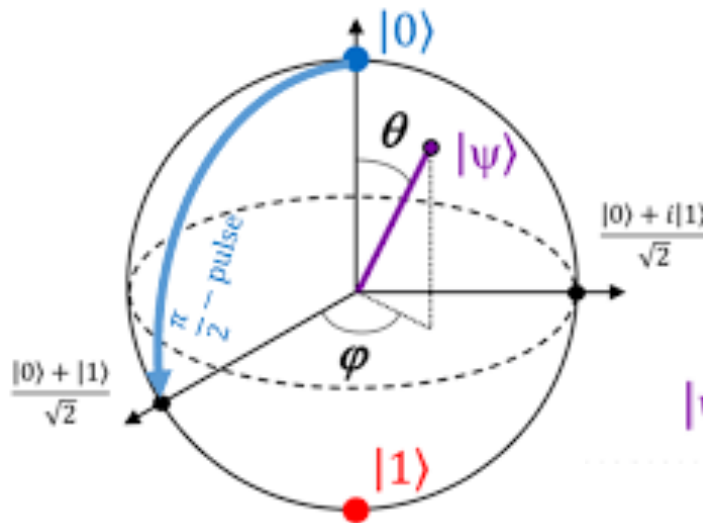
6 cards

- **Ryan's** turn. Play continues until all cards are used up.



# The Physics of Qubit Touchdown

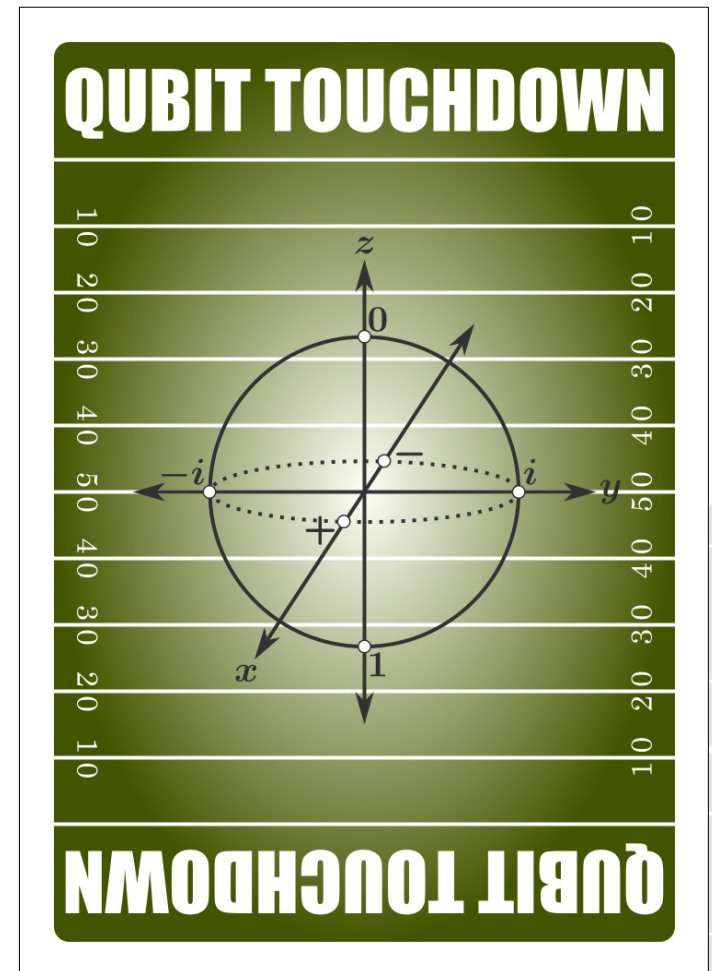
- The back of every action card is a **Bloch sphere**.
- Its North and South poles are 0 and 1, the two possible states of a bit.
- A quantum bit, or qubit, can be any point on the Bloch sphere. Qubit Touchdown uses six of them: 0, 1, +, −, i, −i.
- The positions on the game board correspond to these six states, and the football is a qubit moving between these states.



$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

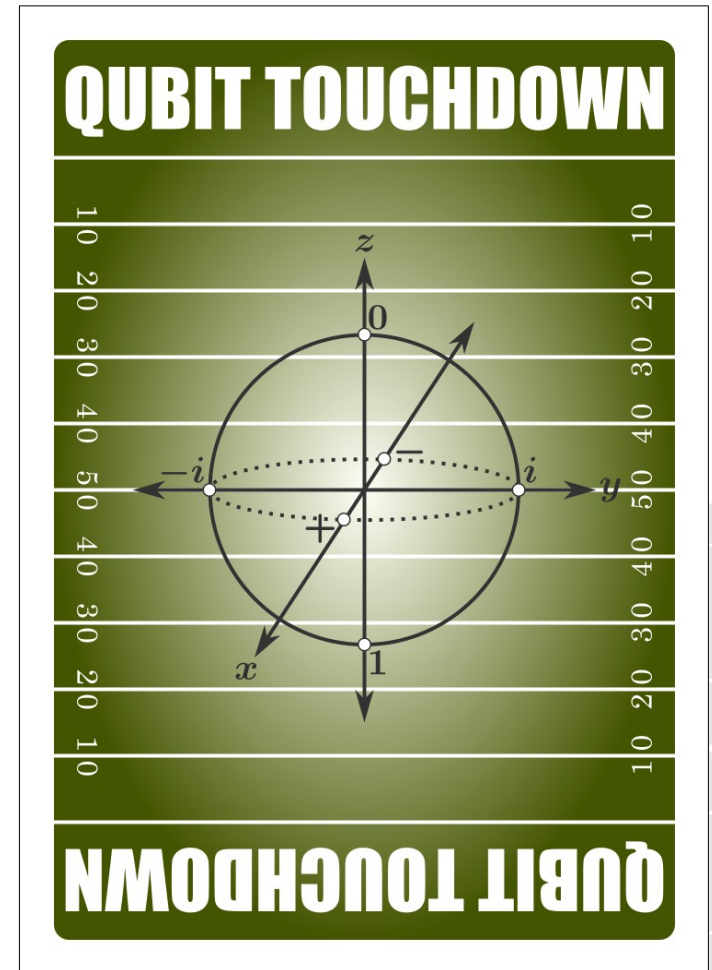
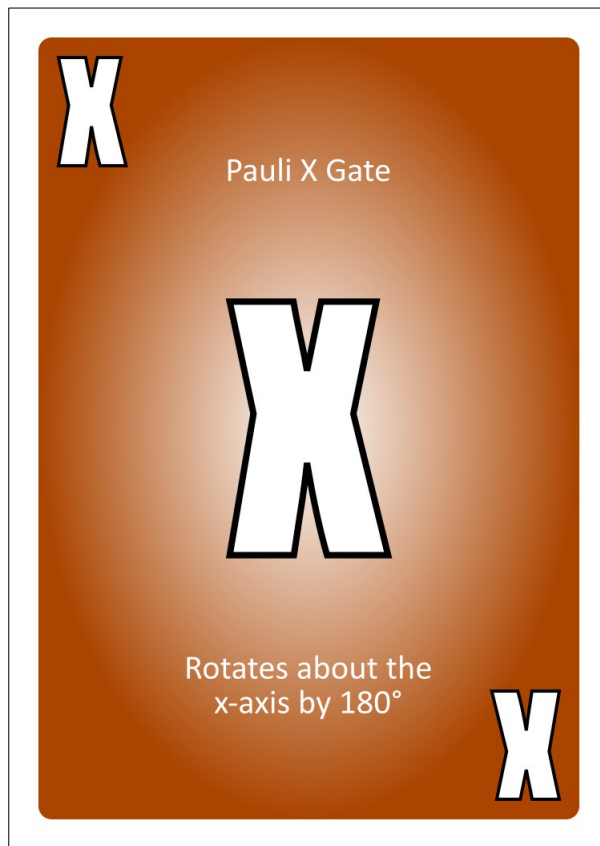
$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$





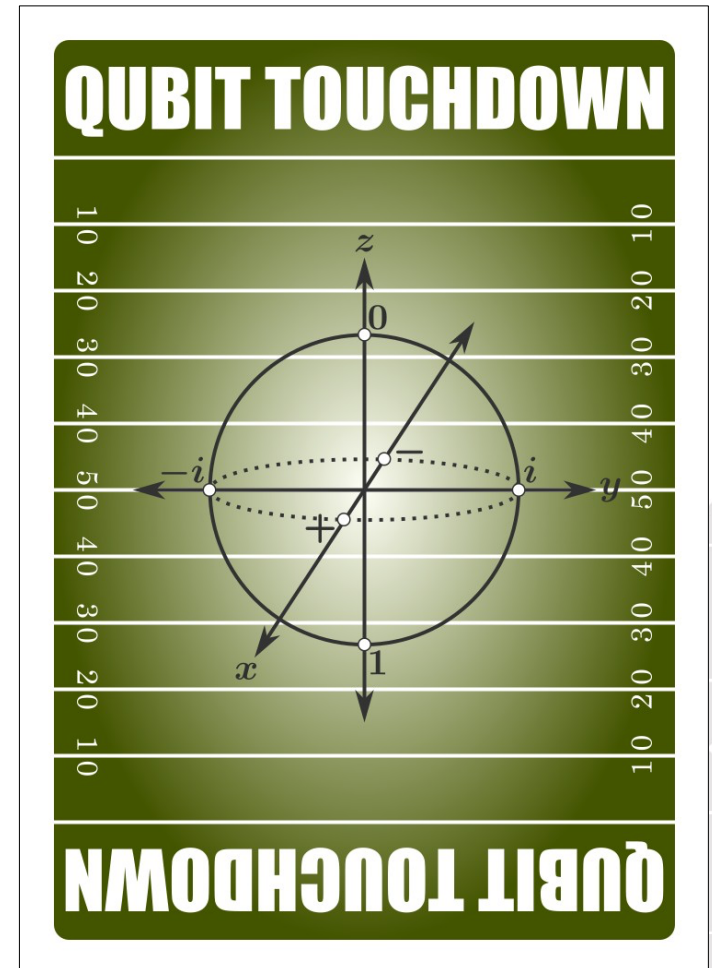
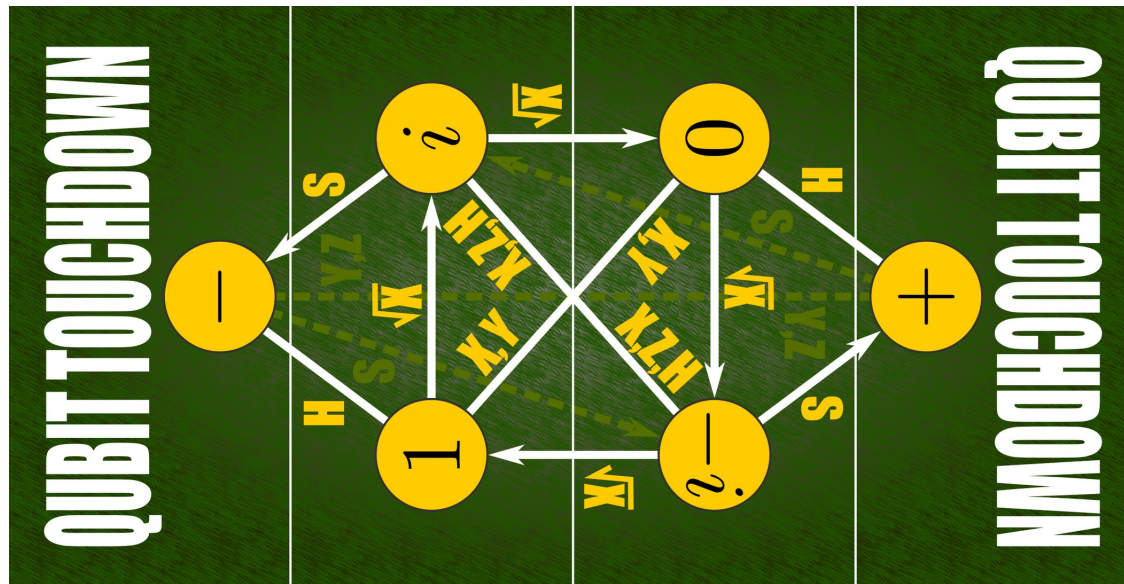
# The Physics of Qubit Touchdown

- Quantum gates change a qubit's state



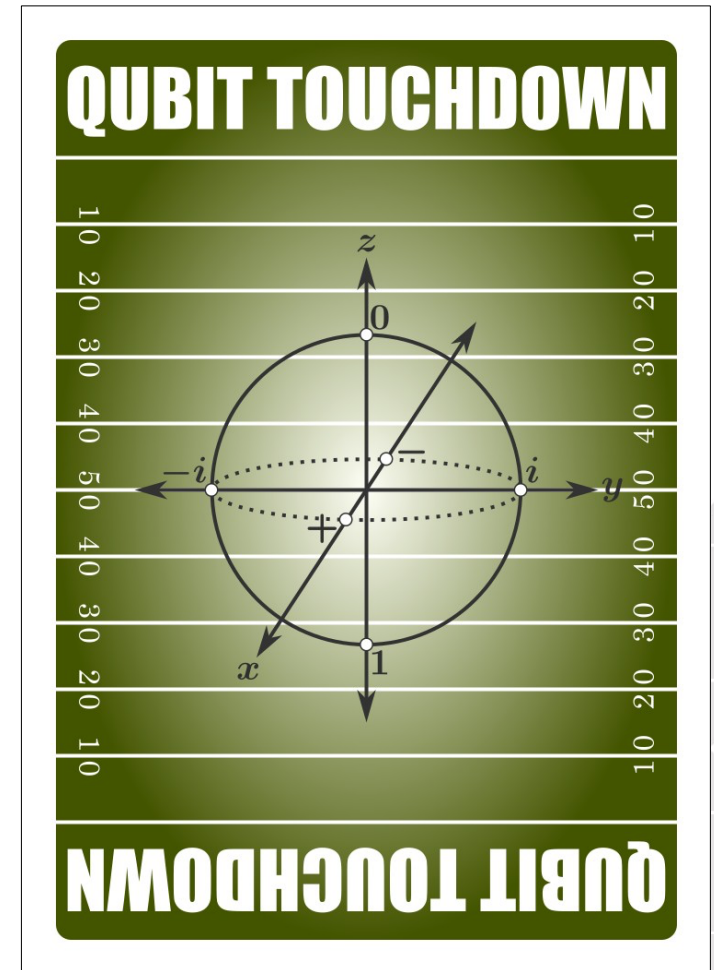
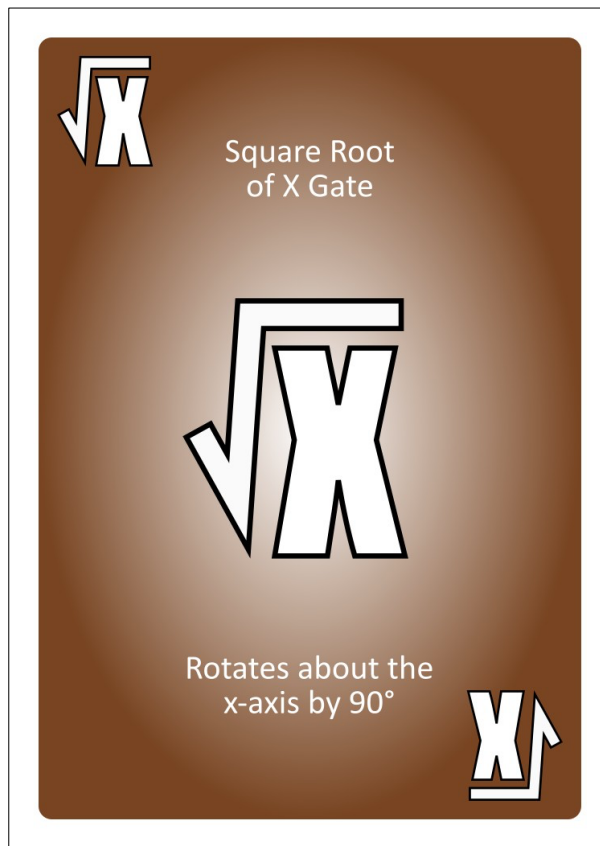
# The Physics of Qubit Touchdown

- Quantum gates change a qubit's state



# The Physics of Qubit Touchdown

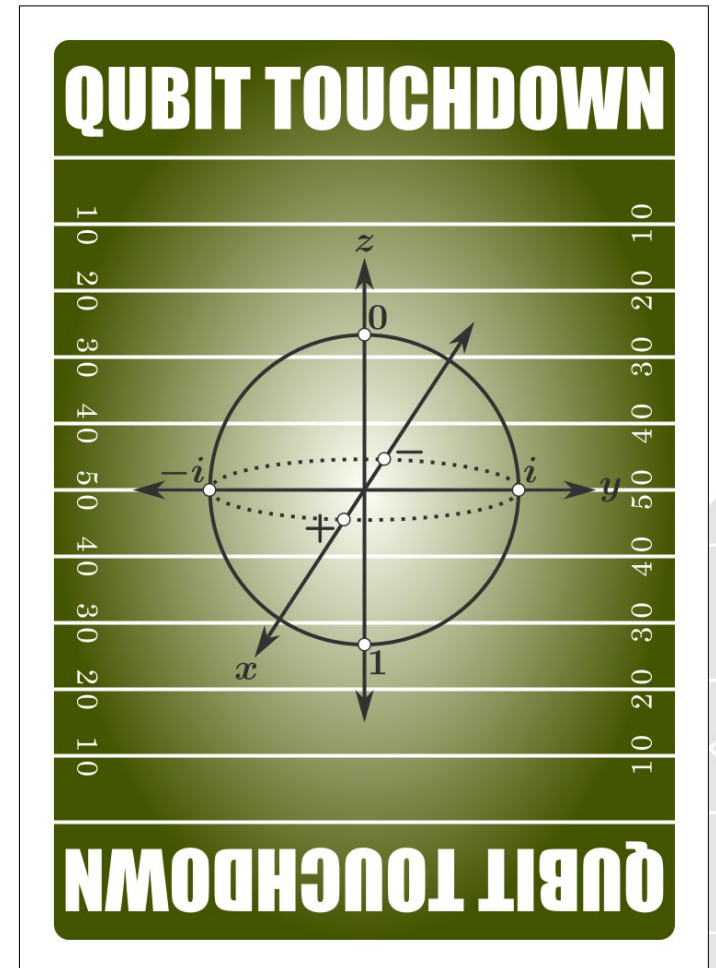
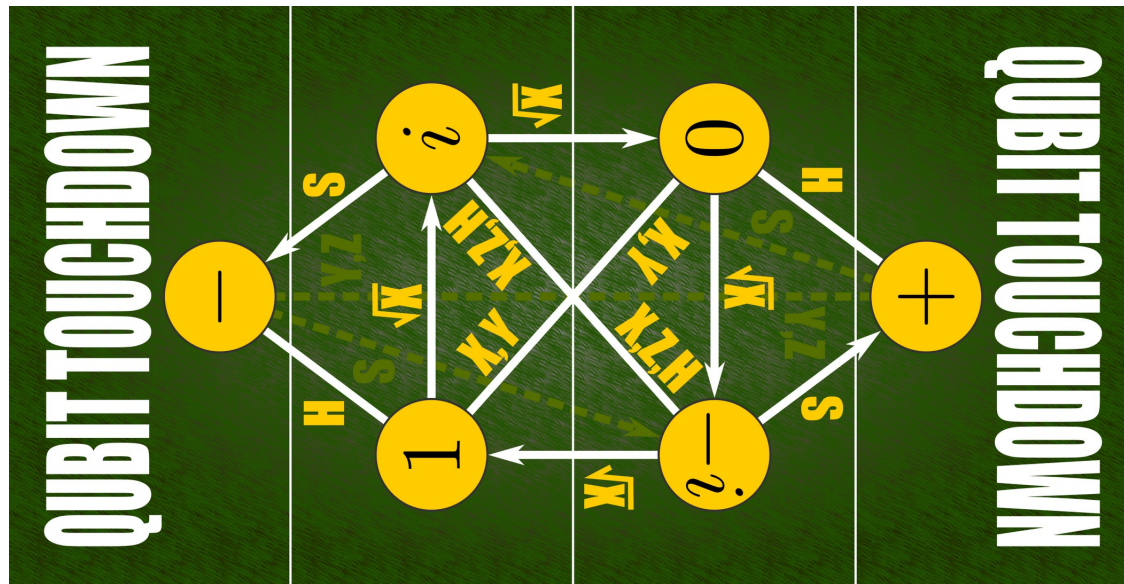
- Quantum gates change a qubit's state





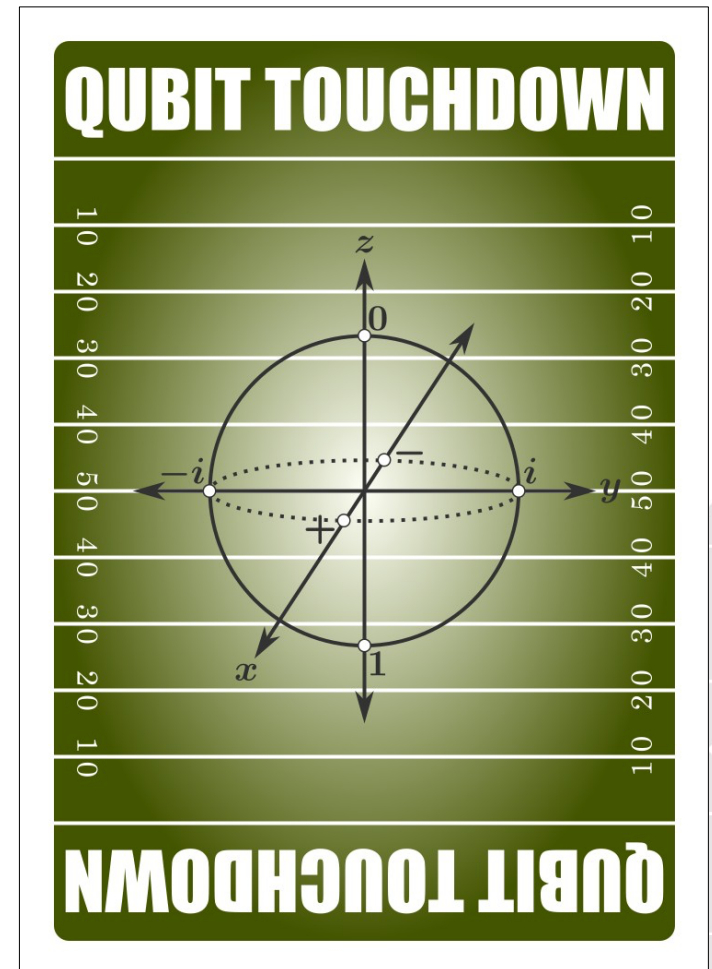
# The Physics of Qubit Touchdown

- Quantum gates change a qubit's state



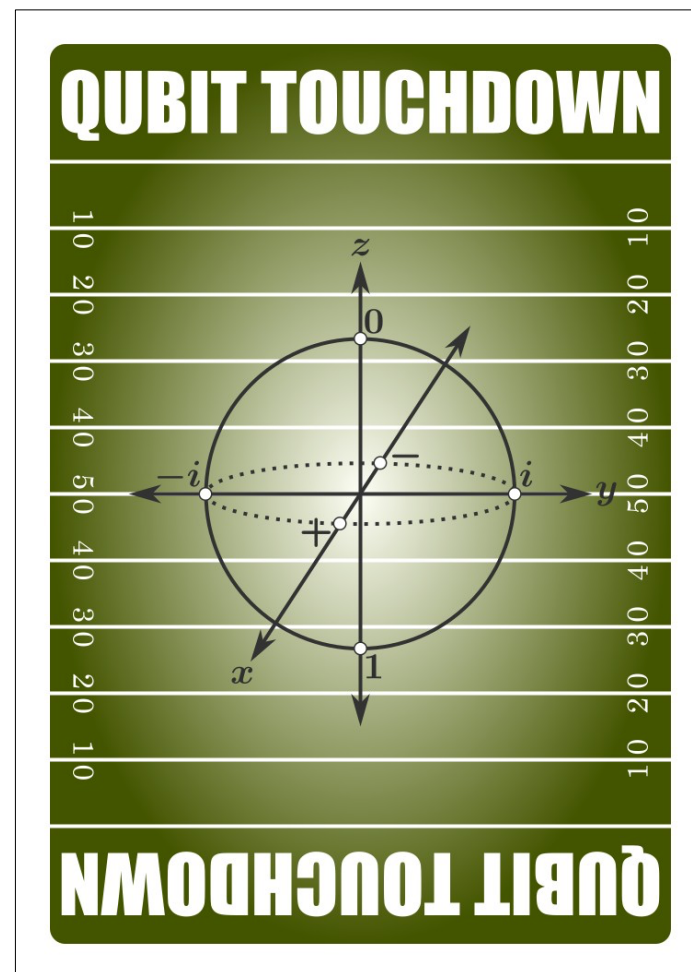
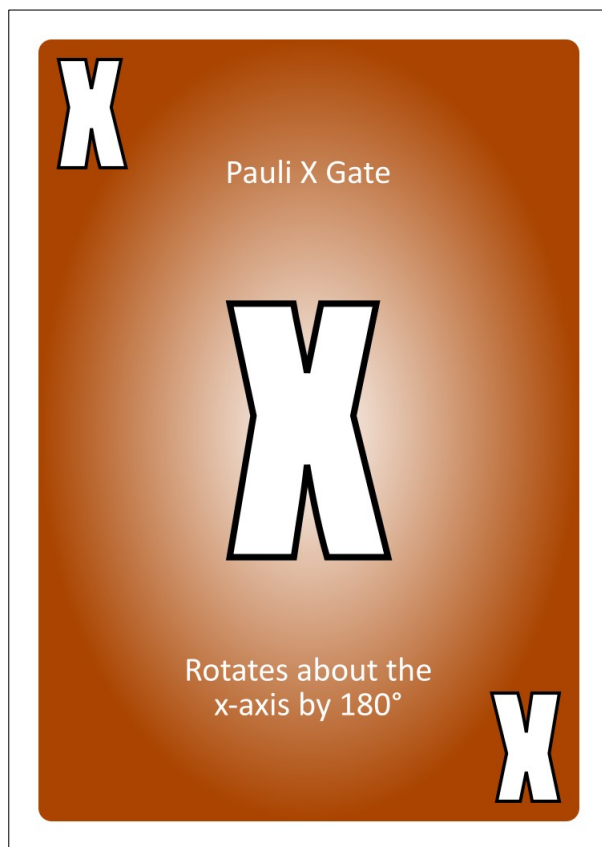
# The Physics of Qubit Touchdown

- Although a qubit can be any point on the Bloch sphere, **measuring its value yields 0 or 1, each with some probability.**
- Since  $+$ ,  $-$ ,  $i$ ,  $-i$  lie on the equator, they are **superpositions, or combinations, of half 0 and half 1.** Measuring them yields 0 or 1, each with 50% probability.
- Kicking off after a touchdown corresponds to a measurement.



# The Physics of Qubit Touchdown

- Quantum gates change a qubit's state



- X gate is equivalent to performing a 180-degree (or  $\pi$  radian) rotation around the X-axis on the Bloch sphere.
- However, 360 degree (or  $2\pi$  radian) rotation introduces a global phase shift of -1 to the qubit's state vector.





# ENTANGLION

The World's First Open Source Quantum Board Game. Master New Galaxies in Your Quest to Construct a Quantum Computer!



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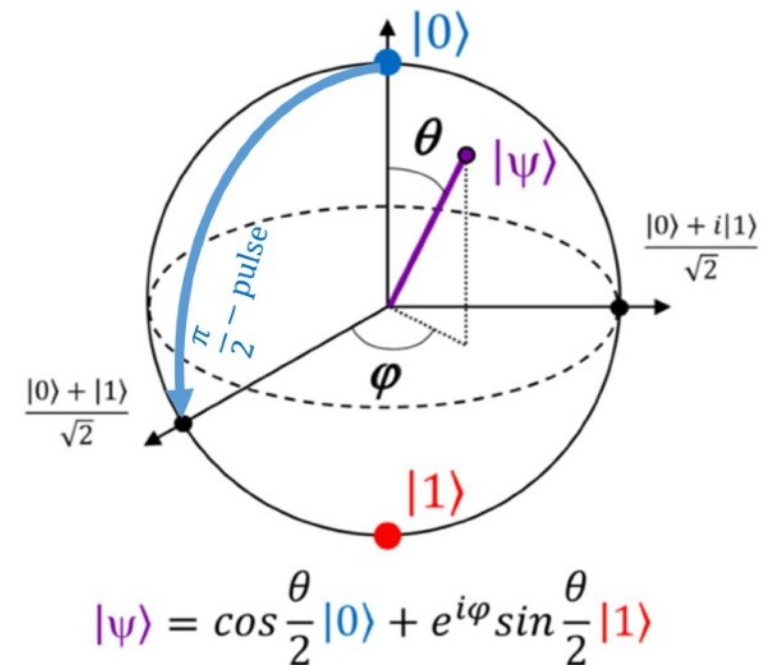
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- Research Experience for Undergraduates
- MS QISE
- K-12 Outreach (SPARCQS)
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Center for  
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*NSF Engineering Research Center*

# Why Quantum Computing?

- Cryptography
  - Mathematics: factoring, hidden subgroup program, discrete logarithm problem
- Optimization
- Search algorithm
- Quantum Machine Learning
  - Quantum Advantages?
    - Learns better with small # of data
    - Faster convergence
    - Less # of parameters
- Quantum simulation
- What are the interesting problems?



# Efficient vs inefficient algorithms

- Efficient: computation time scales polynomially with problem's size.

– (Ex) search  $n^4$ :

- $n=1000$ :  $t = 1$  sec
- $n=1050$ :  $t = 1.2$  sec

$$\left(\frac{1050}{1000}\right)^4 \approx 1.2$$

- Inefficient: computation time scales exponentially.

– (Ex) factoring  $2^n$

- $n=1000$ :  $t = 1$  sec
- $n=1001$ :  $t = 2$  sec
- $n=1006$ :  $t = 1$  min
- $n=1012$ :  $t = 1$  hour
- $n=1050$ :  $t \sim 3.3$  million years

$$\left(\frac{2^{1006}}{2^{1000}}\right) = 2^6 = 64$$

$$\left(\frac{2^{1050}}{2^{1000}}\right) = 2^{50}$$



$$n \qquad 2^n$$

| # of Qubits | Required Bits to Match | Equivalent Classical Computer RAM | Equivalent Classical Computer Processing Time |
|-------------|------------------------|-----------------------------------|-----------------------------------------------|
| 10          | 1024                   | 128 bytes                         | 2.6 $\mu$ s                                   |
| 20          | 1,048,576              | 131 KB                            | 0.26 ms                                       |
| 30          | 1.1 billion            | 134 MB                            | 0.27 seconds                                  |
| 40          | 1.1 trillion           | 137 Gigabytes                     | 4.6 minutes                                   |
| 53          | $9.0 \times 10^{15}$   | 1 Terabyte                        | 625 hours                                     |
| 63          | $9.0 \times 10^{18}$   | 1 Petabyte                        | 73 years                                      |
| 100         | $9.0 \times 10^{30}$   | 1 Exabyte                         | 10 trillion years                             |
| 1,000       | $9.0 \times 10^{301}$  | $1.3 \times 10^{232}$ Exabytes    | $8.5 \times 10^{283}$ years                   |

RAM = Random Access Memory  
There are 8 bits in one byte.

Assume we have a computer with clock speed of 4 GHz, which means it can execute 4 BILLION cycles per second.

# Need transition from classical to quantum:

● 0

● 1

Classical

bits

gates

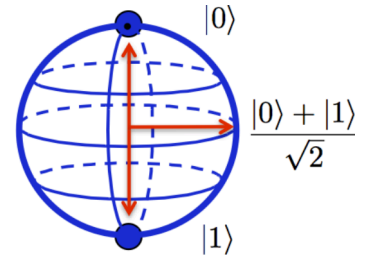
algorithms

Quantum

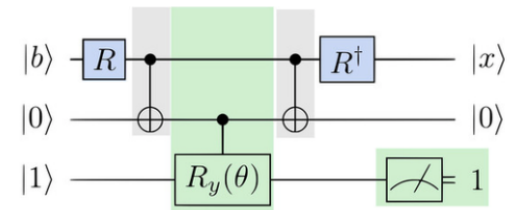
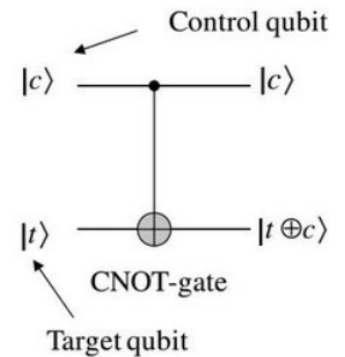
qubits

quantum  
gates

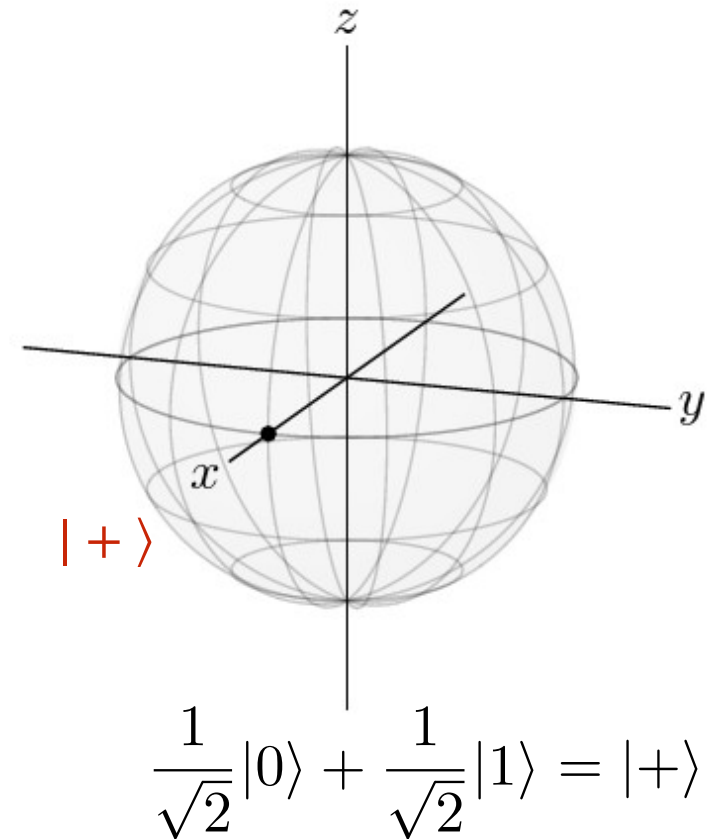
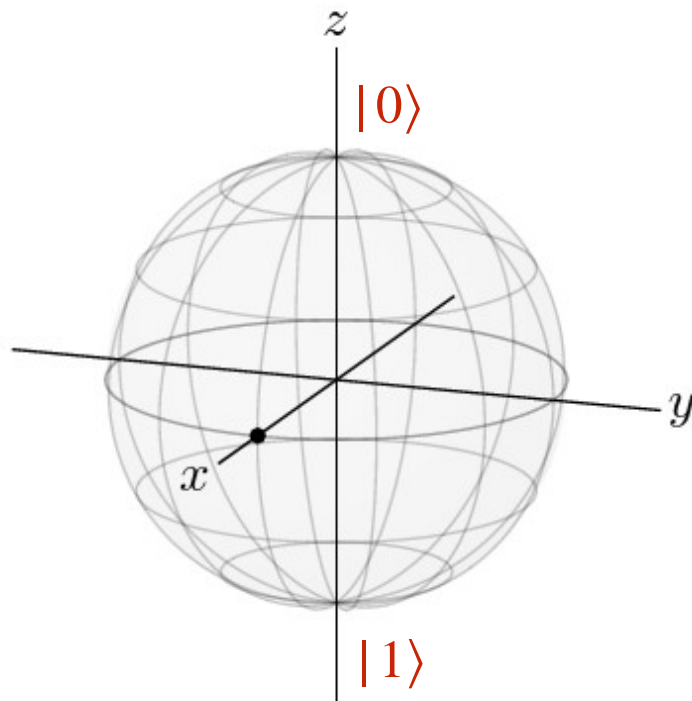
quantum algorithms



**Qubit**



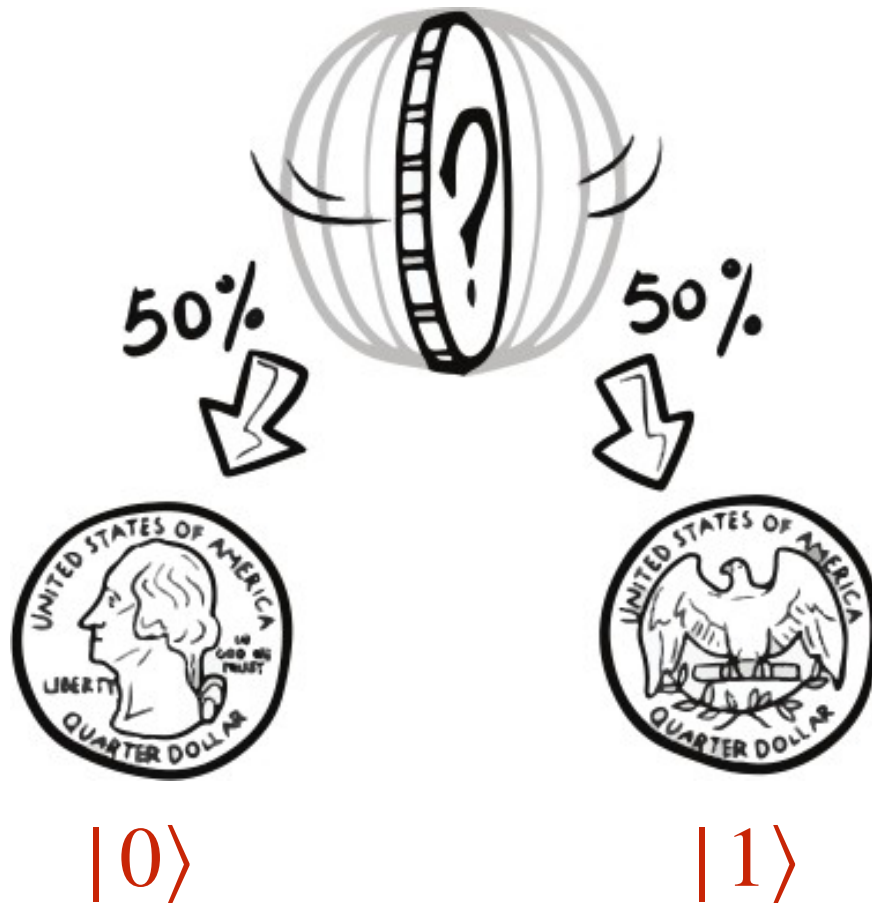
# Quantum Bits (Qubits)



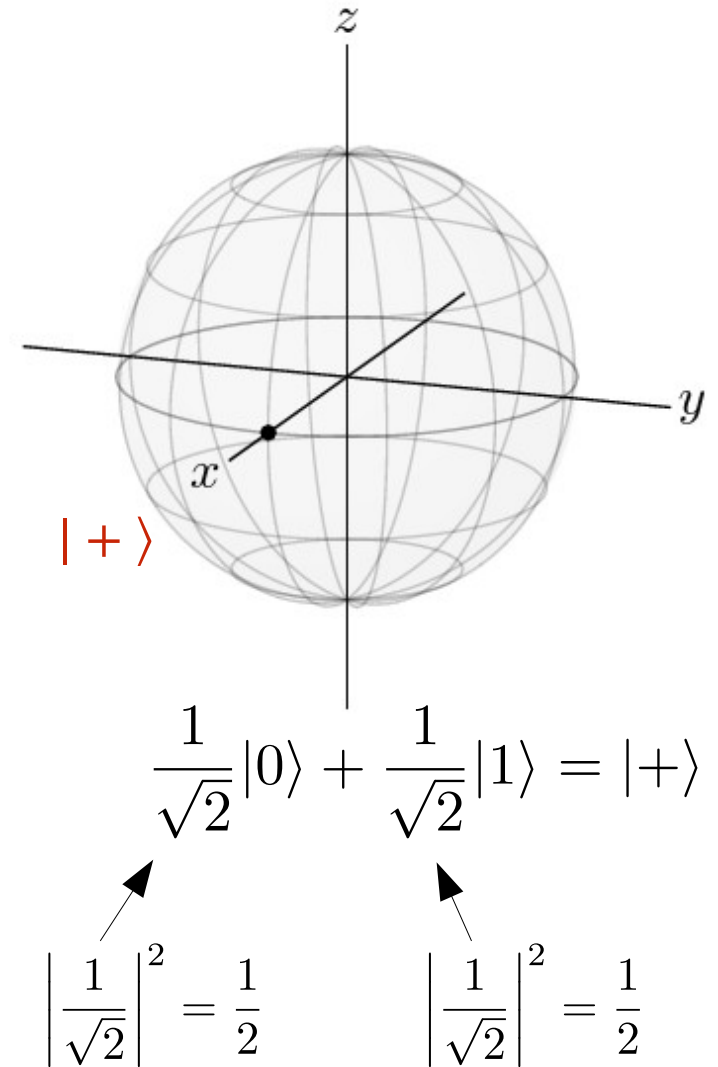




# Quantum Bits (Qubits)

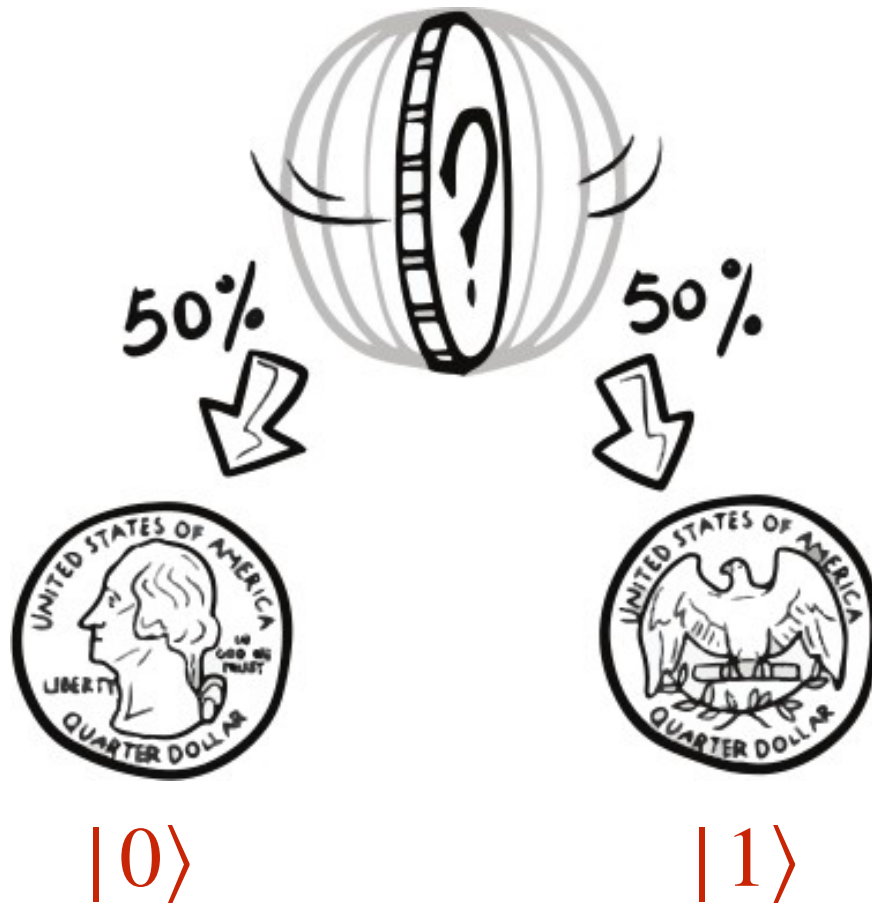


<https://www.epiqc.cs.uchicago.edu/zines-superposition>

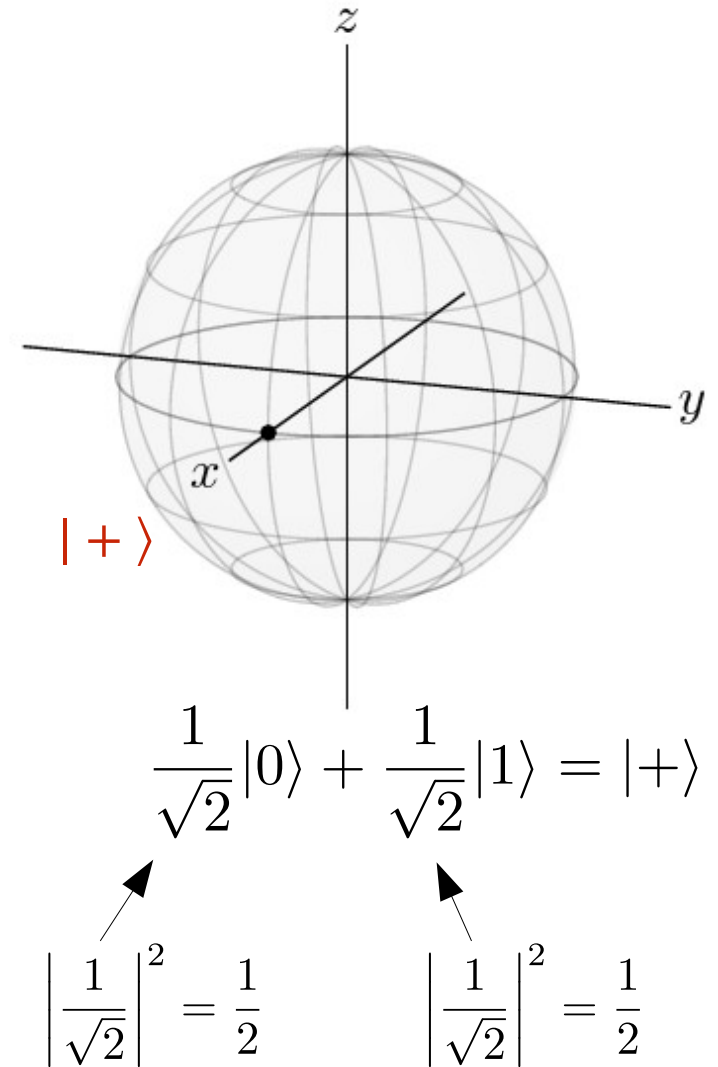




# Quantum Bits (Qubits)

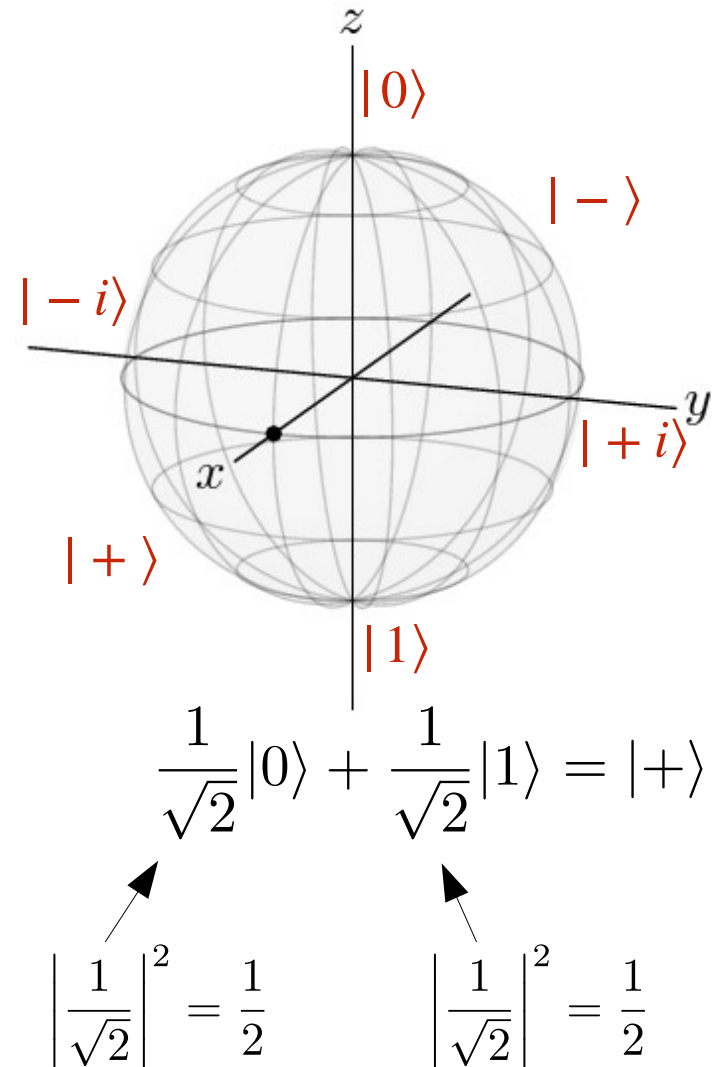


<https://www.epiqc.cs.uchicago.edu/zines-superposition>



# Quantum Bits (Qubits)

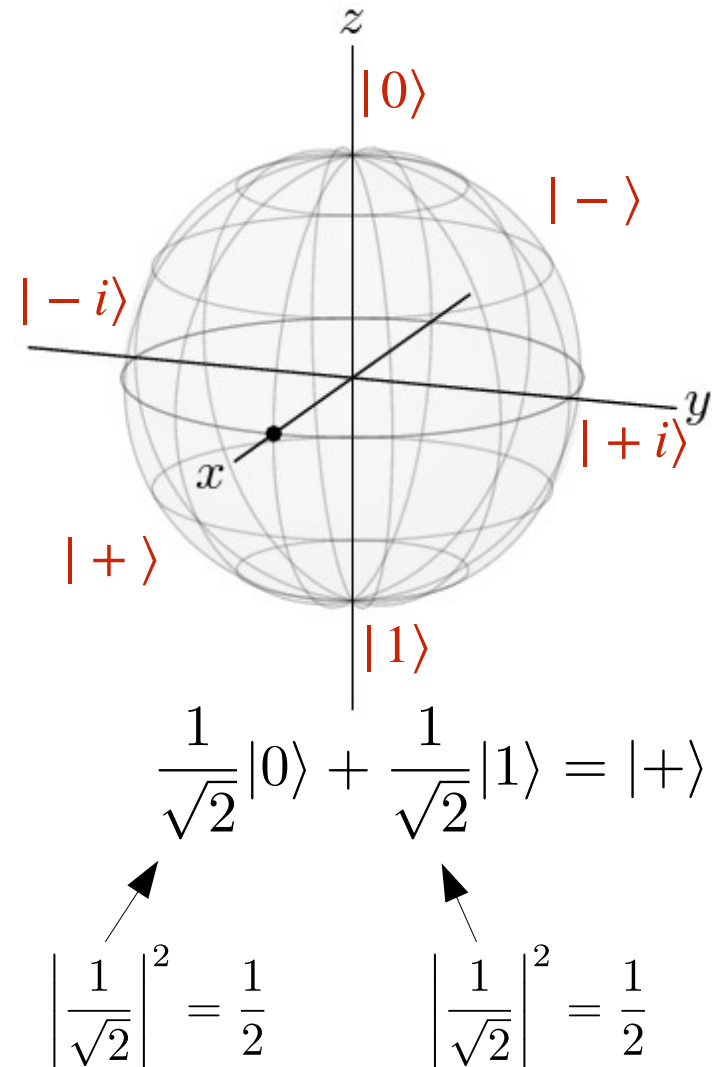
- **Qubit** - quantum bit
- **Superposition** - combination of 0 and 1 ( $|0\rangle$  and  $|1\rangle$ )
- **Amplitude** - coefficient in front of 0 and 1 ( $|0\rangle$  and  $|1\rangle$ )
- **Measurement** - get  $|0\rangle$  or  $|1\rangle$  with probability =  $|\text{amplitude}|^2$ 
  - **Qubit collapses** to  $|0\rangle$  or  $|1\rangle$
- **Normalized** - total probability is 1.
- **Entanglement** - outcome two qubits are intertwined.

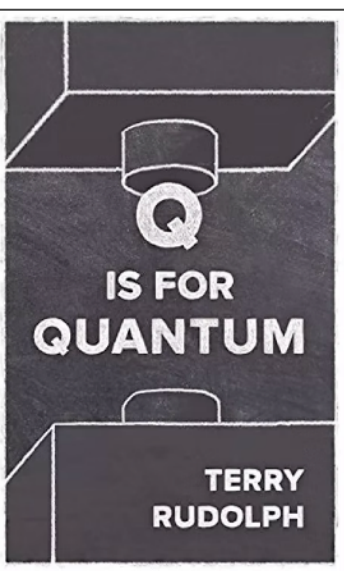




# Quantum Bits (Qubits)

- **Qubit** - quantum bit
- **Superposition** - combination of 0 and 1 ( $|0\rangle$  and  $|1\rangle$ )
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## Q IS FOR QUANTUM, Terry Rudolph

Great introduction to quantum mechanics without using math

Our computers are great and work fine for us.  
Why do we need quantum computers and  
what can we do with them?



|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 1  | 3  | 5  | 7  | 9  | 11 | 13 | 15 |
| 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 |
| 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 |
| 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 2  | 3  | 6  | 7  | 10 | 11 | 14 | 15 |
| 18 | 19 | 22 | 23 | 26 | 27 | 30 | 31 |
| 34 | 35 | 38 | 39 | 42 | 43 | 46 | 47 |
| 50 | 51 | 54 | 55 | 58 | 59 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 4  | 5  | 6  | 7  | 12 | 13 | 14 | 15 |
| 20 | 21 | 22 | 23 | 28 | 29 | 30 | 31 |
| 36 | 37 | 38 | 39 | 44 | 45 | 46 | 47 |
| 52 | 53 | 54 | 55 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |



XXXXXX1

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 1  | 3  | 5  | 7  | 9  | 11 | 13 | 15 |
| 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 |
| 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 |
| 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 |

XXXXX1X

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 2  | 3  | 6  | 7  | 10 | 11 | 14 | 15 |
| 18 | 19 | 22 | 23 | 26 | 27 | 30 | 31 |
| 34 | 35 | 38 | 39 | 42 | 43 | 46 | 47 |
| 50 | 51 | 54 | 55 | 58 | 59 | 62 | 63 |

XXX1XX

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 4  | 5  | 6  | 7  | 12 | 13 | 14 | 15 |
| 20 | 21 | 22 | 23 | 28 | 29 | 30 | 31 |
| 36 | 37 | 38 | 39 | 44 | 45 | 46 | 47 |
| 52 | 53 | 54 | 55 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

XX1XXX

X1XXXX

1XXXXXX

Suppose your number was 43

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 1  | 3  | 5  | 7  | 9  | 11 | 13 | 15 |
| 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 |
| 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 |
| 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 2  | 3  | 6  | 7  | 10 | 11 | 14 | 15 |
| 18 | 19 | 22 | 23 | 26 | 27 | 30 | 31 |
| 34 | 35 | 38 | 39 | 42 | 43 | 46 | 47 |
| 50 | 51 | 54 | 55 | 58 | 59 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 4  | 5  | 6  | 7  | 12 | 13 | 14 | 15 |
| 20 | 21 | 22 | 23 | 28 | 29 | 30 | 31 |
| 36 | 37 | 38 | 39 | 44 | 45 | 46 | 47 |
| 52 | 53 | 54 | 55 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

In base 2: 101011

Suppose your number was 43

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 1  | 3  | 5  | 7  | 9  | 11 | 13 | 15 |
| 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 |
| 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 |
| 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 2  | 3  | 6  | 7  | 10 | 11 | 14 | 15 |
| 18 | 19 | 22 | 23 | 26 | 27 | 30 | 31 |
| 34 | 35 | 38 | 39 | 42 | 43 | 46 | 47 |
| 50 | 51 | 54 | 55 | 58 | 59 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 4  | 5  | 6  | 7  | 12 | 13 | 14 | 15 |
| 20 | 21 | 22 | 23 | 28 | 29 | 30 | 31 |
| 36 | 37 | 38 | 39 | 44 | 45 | 46 | 47 |
| 52 | 53 | 54 | 55 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

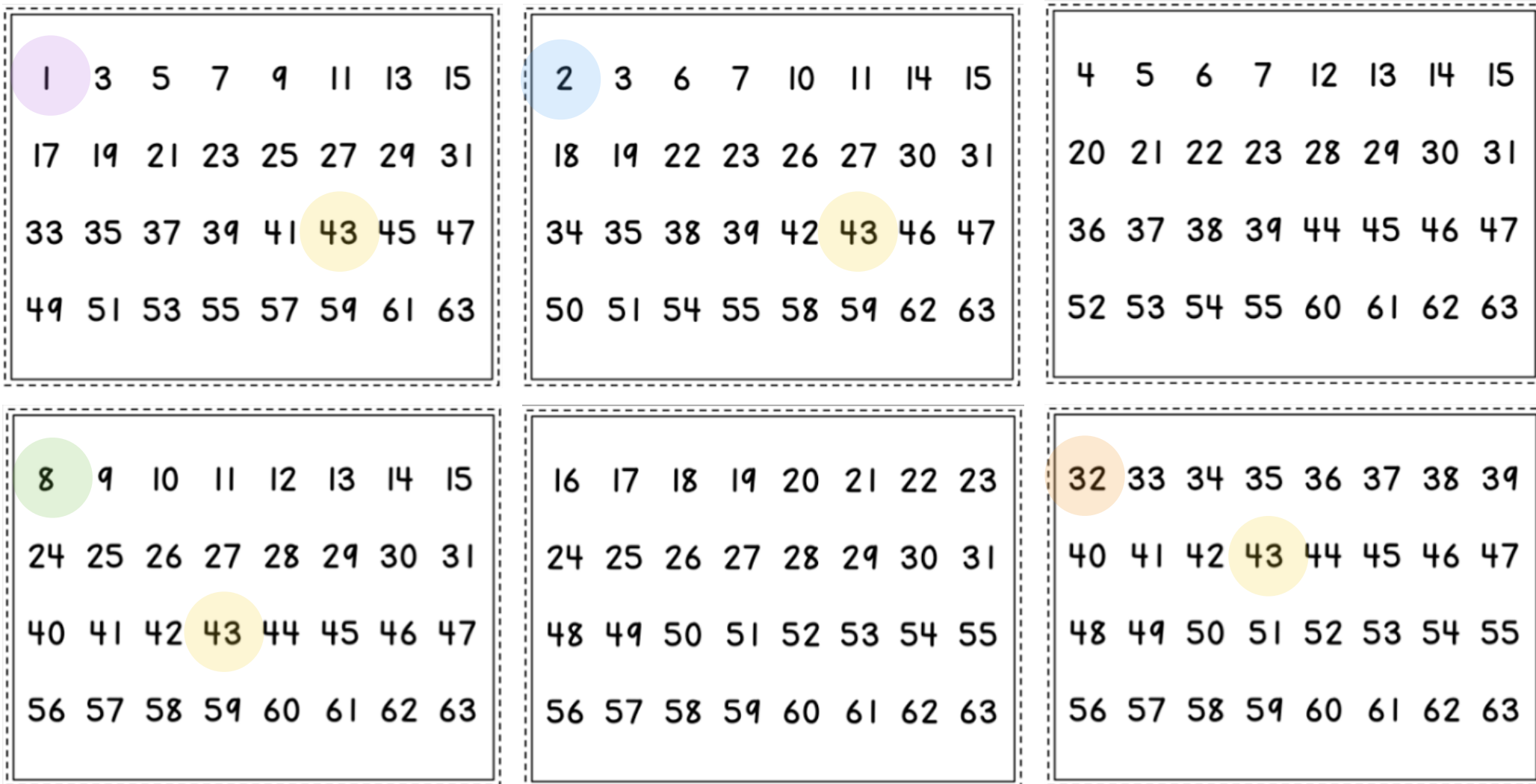
|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

|    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

In base 2:  $101011 = 100000 + 001000 + 000010 + 000001$



Suppose your number was 43



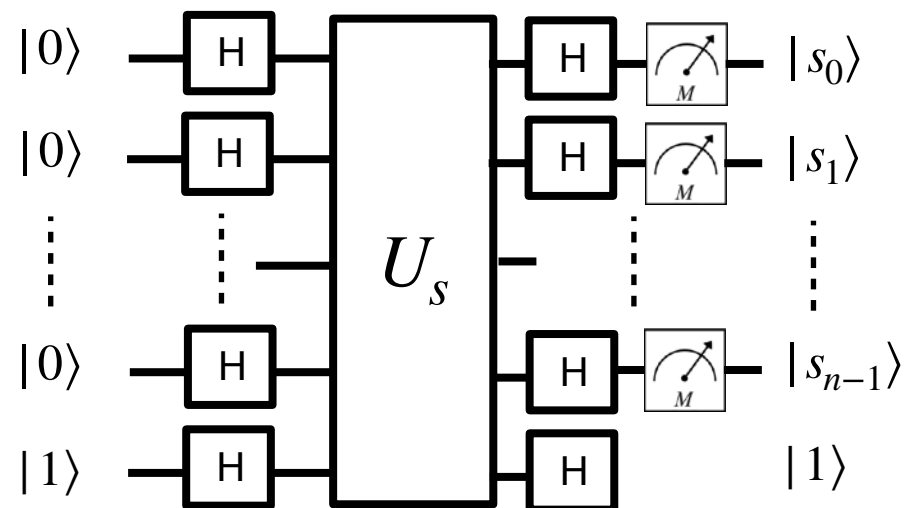
In base 2:  $101011 = 100000 + 001000 + 000010 + 000001$

In base 10:  $= 32 + 8 + 2 + 1$   
 $= 43$

Is there a way to find out the answer  
by asking less than 6 questions?

# Bernstein-Vazirani Algorithm

- A  $n$ -bit function  $f: \{0,1\}^{\otimes n} \longrightarrow \{0,1\}$ , which outputs a single bit, is guaranteed to be of the form  $f_s(x) = x \cdot s$ , where  $s$  is an unknown  $n$ -bit string and  $x \cdot s = x_0s_0 + \dots + x_{n-1}s_{n-1} = \sum_{i=0}^{n-1} x_i s_i \pmod{2}$ . Find the unknown string  $s = (s_0s_1 \dots s_{n-1})$ .
- Best classical algorithm uses  $\mathcal{O}(n)$  calls to  $f_s(x) = x \cdot s \pmod{2}$ . Each query gives one bit of information of  $s$  (because  $f$  outputs one bit).
- How do we find  $s$  with less than  $n$  queries?  $\rightarrow$  Use superposition (over all possible input bit strings)





# Inner Product

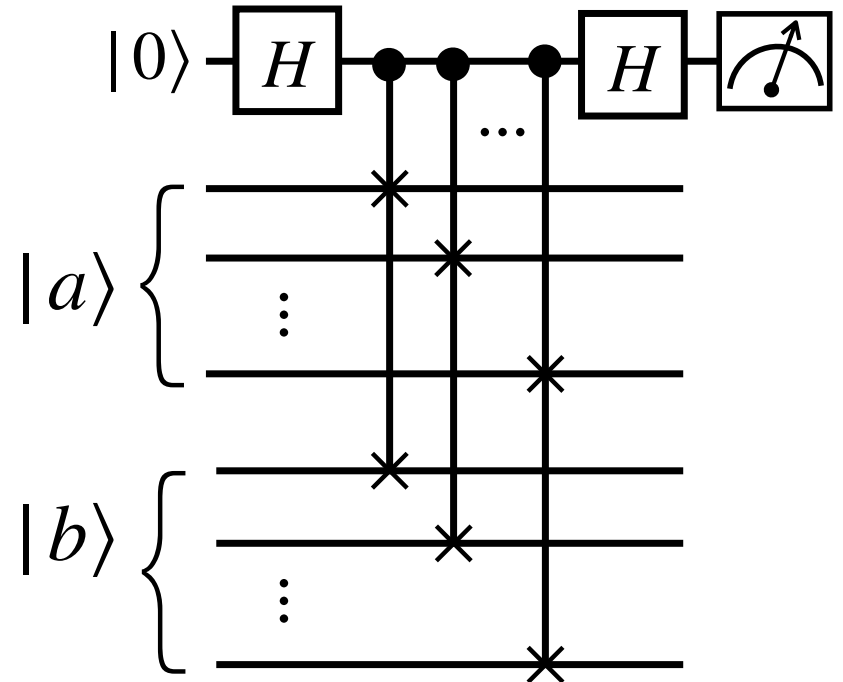
$$\vec{a} = (a_1, a_2, \dots, a_{1024})$$

$$\vec{b} = (b_1, b_2, \dots, b_{1024})$$

$$\vec{a} \cdot \vec{b} = a_1 b_1 + a_2 b_2 + \dots + a_{1024} b_{1024}$$

How many operations

= 1024 multiplications + 1023 additions



$|a\rangle$  : 10 qubits are needed to embed  $\vec{a} = (a_1, a_2, \dots, a_{1024})$

$|b\rangle$  : 10 qubits are needed to embed  $\vec{b} = (b_1, b_2, \dots, b_{1024})$

$|0\rangle$  : 1 additional qubit as a registry

$$2^{10} = 1024$$

12 operations are needed.

# Proof: Inner product

$$|a\rangle \otimes |b\rangle = |a\rangle |b\rangle$$

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

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

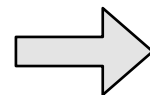
$$(2) \quad SWAP H(|0\rangle |a\rangle |b\rangle) = \frac{1}{\sqrt{2}} SWAP(|0\rangle + |1\rangle) |a\rangle |b\rangle = \frac{1}{\sqrt{2}} (|0\rangle |a\rangle |b\rangle + |1\rangle |b\rangle |a\rangle)$$

$$(3) \quad \begin{aligned} |\psi\rangle &= H SWAP H(|0\rangle |a\rangle |b\rangle) = \frac{1}{\sqrt{2}} H(|0\rangle |a\rangle |b\rangle + |1\rangle |b\rangle |a\rangle) \\ &= \frac{1}{2} |0\rangle (|a\rangle |b\rangle + |b\rangle |a\rangle) + \frac{1}{2} |1\rangle (|a\rangle |b\rangle - |b\rangle |a\rangle) \end{aligned}$$

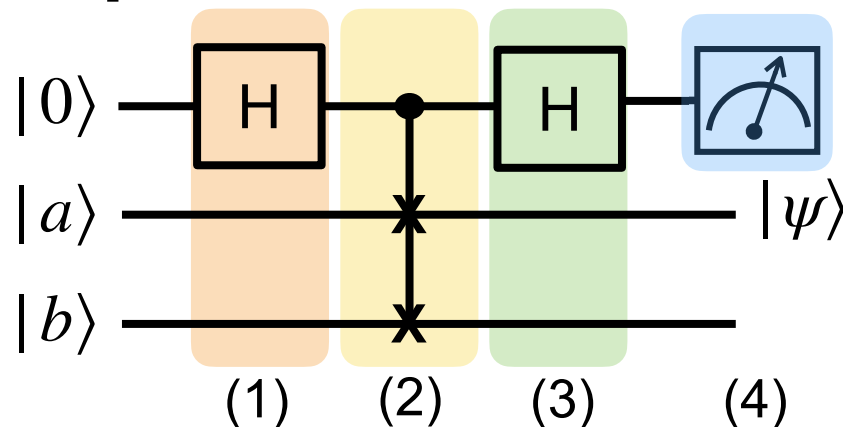
sum of the “unswapped” and the “swapped”

difference

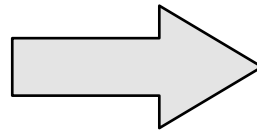
$$(4) \quad \begin{aligned} P(0) &= |(\langle 0 \otimes I) |\psi\rangle|^2 = \frac{1}{2} - \frac{1}{2} |\langle a | b \rangle|^2 \\ P(1) &= |(\langle 1 \otimes I) |\psi\rangle|^2 = \frac{1}{2} + \frac{1}{2} |\langle a | b \rangle|^2 \end{aligned}$$



$$P(1) - P(0) = |\langle a | b \rangle|^2$$



## Using vector notation



## Using Dirac bracket notation

$$\vec{a} = \left( \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}} \right)$$

$$\vec{b} = (1, 0)$$

$$\begin{aligned} \vec{a} \cdot \vec{b} &= \frac{1}{\sqrt{2}} \cdot 1 + \frac{1}{\sqrt{2}} \cdot 0 \\ &= \frac{1}{\sqrt{2}} \approx 0.707 \end{aligned}$$

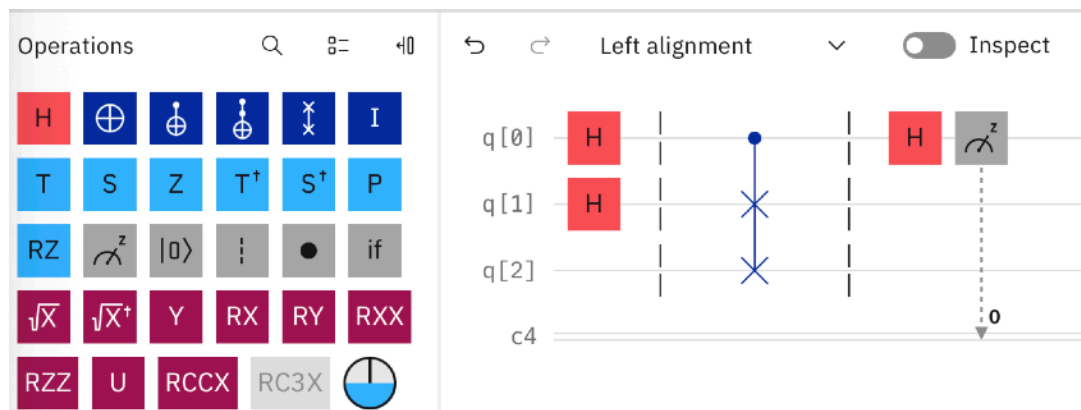
$$|\vec{a} \cdot \vec{b}|^2 = 0.5$$

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

$$|b\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = |0\rangle \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

$$\begin{aligned} \langle a | b \rangle &= \frac{1}{\sqrt{2}} \cdot 1 + \frac{1}{\sqrt{2}} \cdot 0 \\ &= \frac{1}{\sqrt{2}} \approx 0.707 \end{aligned}$$

$$|\langle a | b \rangle|^2 = P(1) - P(0) = 0.5$$



IBM Quantum  
Composer



# The First Wave of Quantum Machine Learning?

PRL 103, 150502 (2009)

PHYSICAL REVIEW LETTERS

week ending  
9 OCTOBER 2009



## Quantum Algorithm for Linear Systems of Equations

Aram W. Harrow,<sup>1</sup> Avinatan Hassidim,<sup>2</sup> and Seth Lloyd<sup>3</sup>

<sup>1</sup>*Department of Mathematics, University of Bristol, Bristol, BS8 1TW, United Kingdom*

<sup>2</sup>*Research Laboratory for Electronics, MIT, Cambridge, Massachusetts 02139, USA*

<sup>3</sup>*Research Laboratory for Electronics and Department of Mechanical Engineering, MIT, Cambridge, Massachusetts 02139, USA*

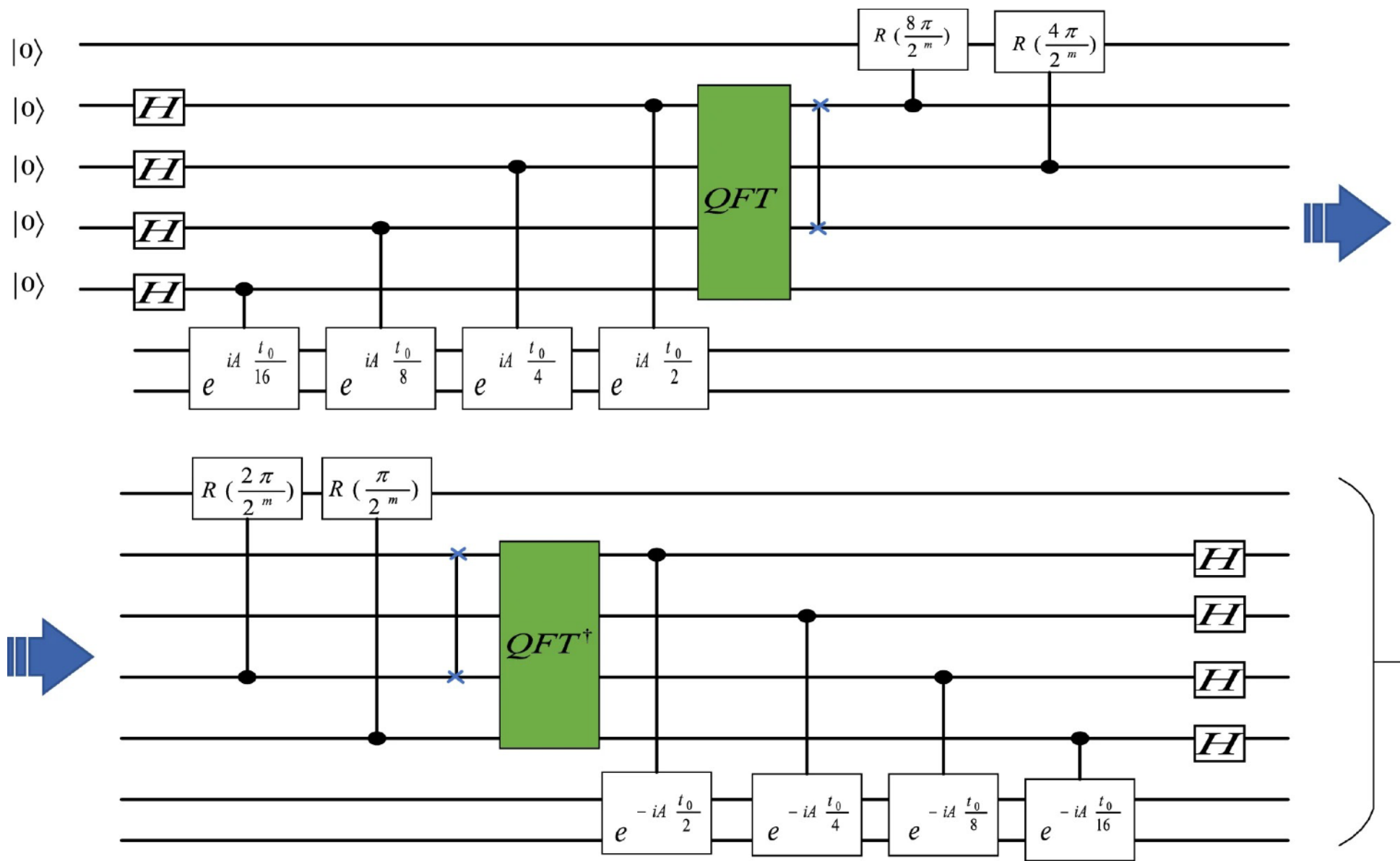
(Received 5 July 2009; published 7 October 2009)

Solving linear systems of equations is a common problem that arises both on its own and as a subroutine in more complex problems: given a matrix  $A$  and a vector  $\vec{b}$ , find a vector  $\vec{x}$  such that  $A\vec{x} = \vec{b}$ . We consider the case where one does not need to know the solution  $\vec{x}$  itself, but rather an approximation of the expectation value of some operator associated with  $\vec{x}$ , e.g.,  $\vec{x}^\dagger M \vec{x}$  for some matrix  $M$ . In this case, when  $A$  is sparse,  $N \times N$  and has condition number  $\kappa$ , the fastest known classical algorithms can find  $\vec{x}$  and estimate  $\vec{x}^\dagger M \vec{x}$  in time scaling roughly as  $N\sqrt{\kappa}$ . Here, we exhibit a quantum algorithm for estimating  $\vec{x}^\dagger M \vec{x}$  whose runtime is a polynomial of  $\log(N)$  and  $\kappa$ . Indeed, for small values of  $\kappa$  [i.e.,  $\text{poly} \log(N)$ ], we prove (using some common complexity-theoretic assumptions) that any classical algorithm for this problem generically requires exponentially more time than our quantum algorithm.

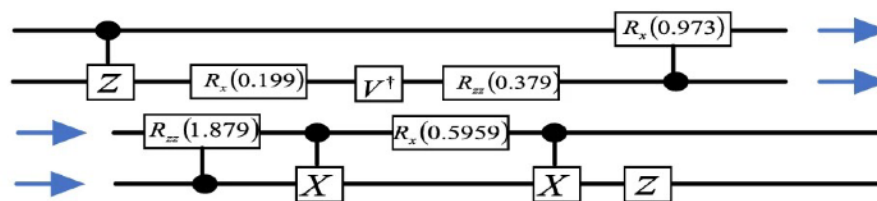
$$Ax = b$$

Complexity of inversion of a regular matrix= $O(N^3)$

Complexity of inversion of a sparse matrix= $O(N)$



$$\left[ \begin{array}{c} \text{---} \\ \text{---} \end{array} \begin{array}{c} \boxed{e^{-iA \frac{t_0}{16}}} \\ \end{array} \begin{array}{c} \text{---} \\ \text{---} \end{array} \right] =$$



DFT:  $N^2$   
 FFT:  $N \log_2 N$   
 QFT:  $(\log_2 N)^2$

# Experimental realization

PRL 110, 230501 (2013)

PHYSICAL REVIEW LETTERS

week ending  
7 JUNE 2013



## Experimental Quantum Computing to Solve Systems of Linear Equations

X.-D. Cai,<sup>1</sup> C. Weedbrook,<sup>2</sup> Z.-E. Su,<sup>1</sup> M.-C. Chen,<sup>1</sup> Mile Gu,<sup>3,4</sup> M.-J. Zhu,<sup>1</sup> Li Li,<sup>1,\*</sup> Nai-Le Liu,<sup>1,†</sup>  
Chao-Yang Lu,<sup>1,‡</sup> and Jian-Wei Pan<sup>1</sup>

<sup>1</sup>*Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics,  
University of Science and Technology of China, Hefei, Anhui 230026, China*

<sup>2</sup>*Center for Quantum Information and Quantum Control, Department of Electrical and Computer Engineering,  
and Department of Physics, University of Toronto, Toronto M5S 3G4, Canada*

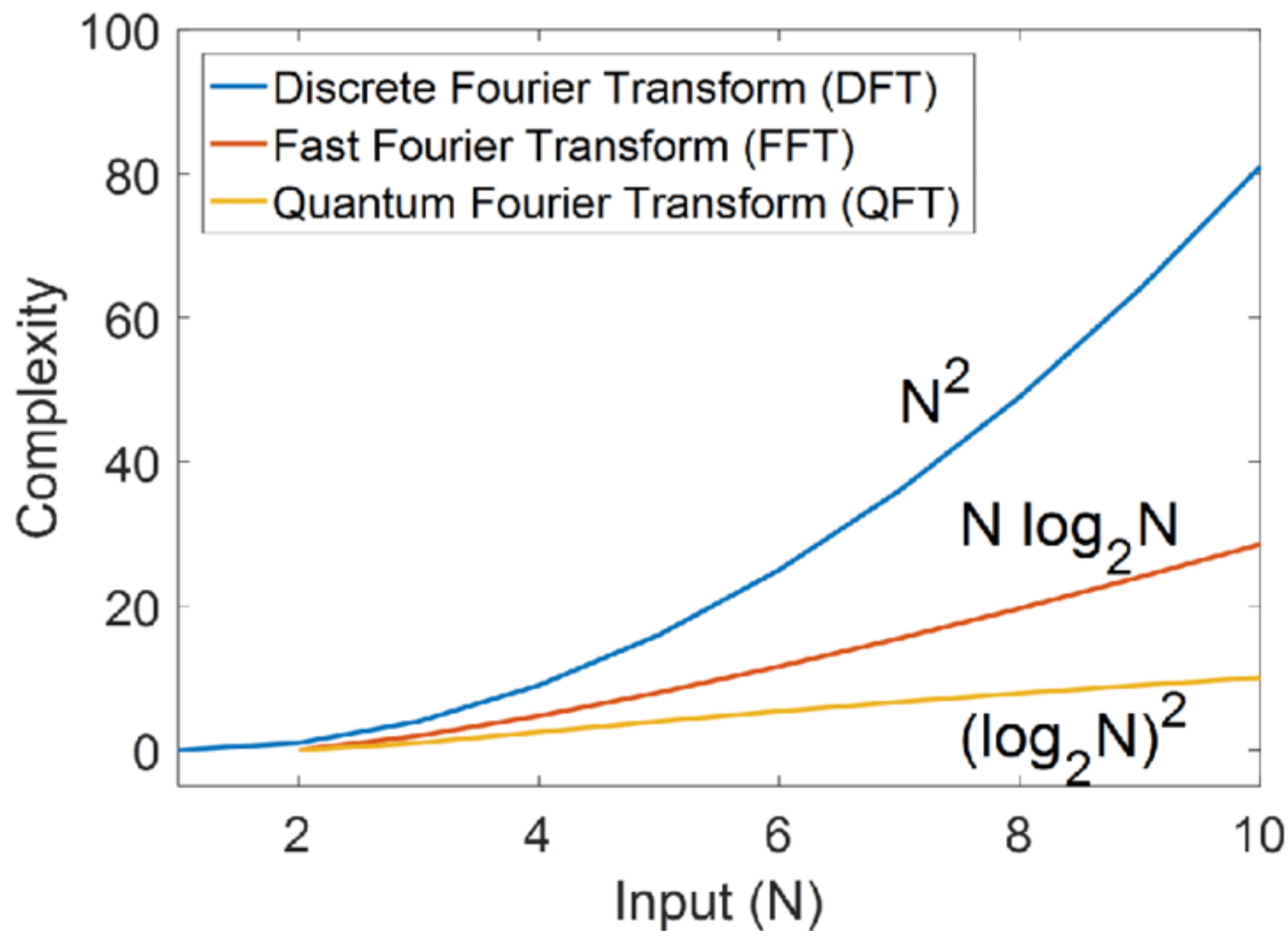
<sup>3</sup>*Centre for Quantum Technologies, National University of Singapore, Singapore 117543*

<sup>4</sup>*Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing 100084, China*  
(Received 6 March 2013; published 6 June 2013)

Solving linear systems of equations is ubiquitous in all areas of science and engineering. With rapidly growing data sets, such a task can be intractable for classical computers, as the best known classical algorithms require a time proportional to the number of variables  $N$ . A recently proposed quantum algorithm shows that quantum computers could solve linear systems in a time scale of order  $\log(N)$ , giving an exponential speedup over classical computers. Here we realize the simplest instance of this algorithm, solving  $2 \times 2$  linear equations for various input vectors on a quantum computer. We use four quantum bits and four controlled logic gates to implement every subroutine required, demonstrating the working principle of this algorithm.

["A two-qubit photonic quantum processor and its application to solving systems of linear equations". Scientific Reports. 4: 6115.](#)  
["Experimental realization of quantum algorithm for solving linear systems of equations". Physical Review A. 89 \(2\): 022313](#)

[Quantum algorithms for systems of linear equations inspired by adiabatic quantum computing, Phys.Rev.Lett. 122 \(2019\) 6, 060504](#)  
====> ["Experimental realization of quantum algorithms for a linear system inspired by adiabatic quantum computing". Phys. Rev. A 99, 012320.](#) 8 dimensional linear equation.





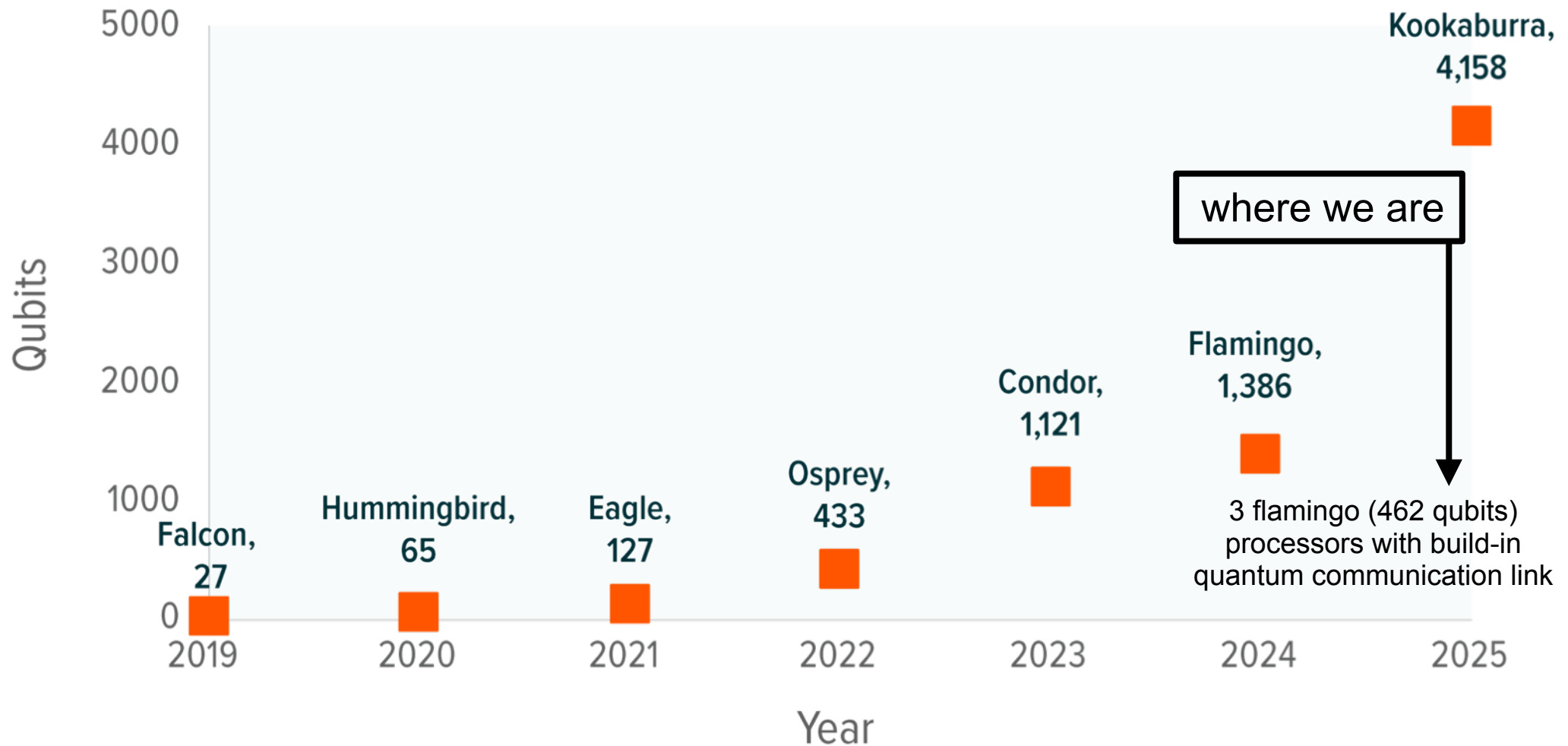
# A few popular tools for quantum simulation

- Qiskit (IBM)
  - IBM Quantum Composer
  - IBM Quantum Platform
- PennyLane and Strawberry Fields (Xanadu)
- TensorFlowQuantum (google)
- CUDA Quantum (NVIDIA)
- TensorCircuit

Attention Is All You Need  
1706.03762

# IBM QUANTUM PROCESSORS ROADMAP

Sources: Global X analysis of information derived from: IBM. (2022). Our new 2022 development roadmap.



Note: 2022 onwards includes planned processor launches.

IBM has been following a quantum-computing road map that roughly doubles the number of qubits every year.

# A quantum computing partnership with the University of Chicago and the University of Tokyo

The commitment, to be signed May 21 on the sidelines of the G7 and U.S.-Japan Leaders' Meeting, aims to advance development of a fault-tolerant quantum computer by supporting research, entrepreneurship and workforce training.

May 17, 2023 · 2 min read

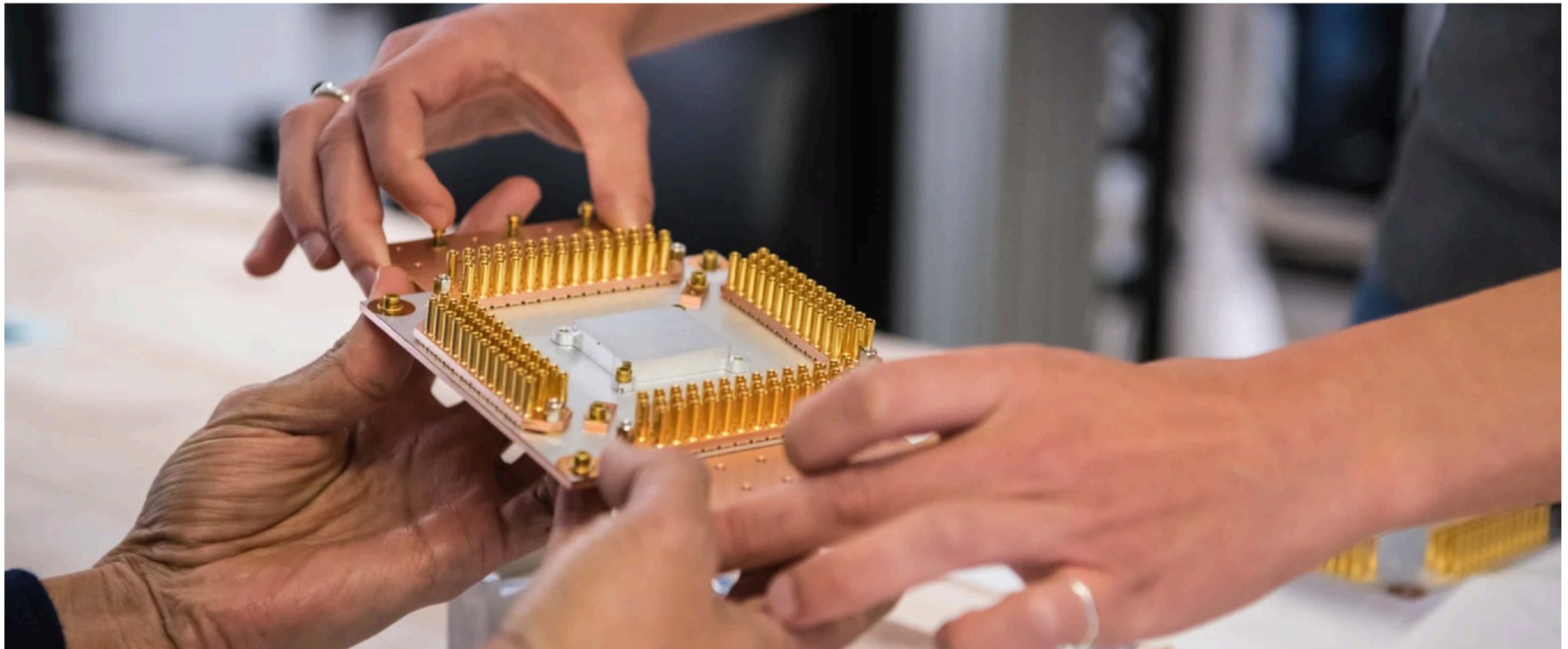


**Charina Chou**  
Director and COO,  
Google Quantum AI



**Hartmut Neven**  
VP, Google Quantum AI

 Share



# Quantum computers are hard to build

- Qubits, unlike classical bits, need to interact strongly among themselves to form entangled states, which in turn form the basis for computation in quantum computers. But to achieve this experimentally is incredibly hard.



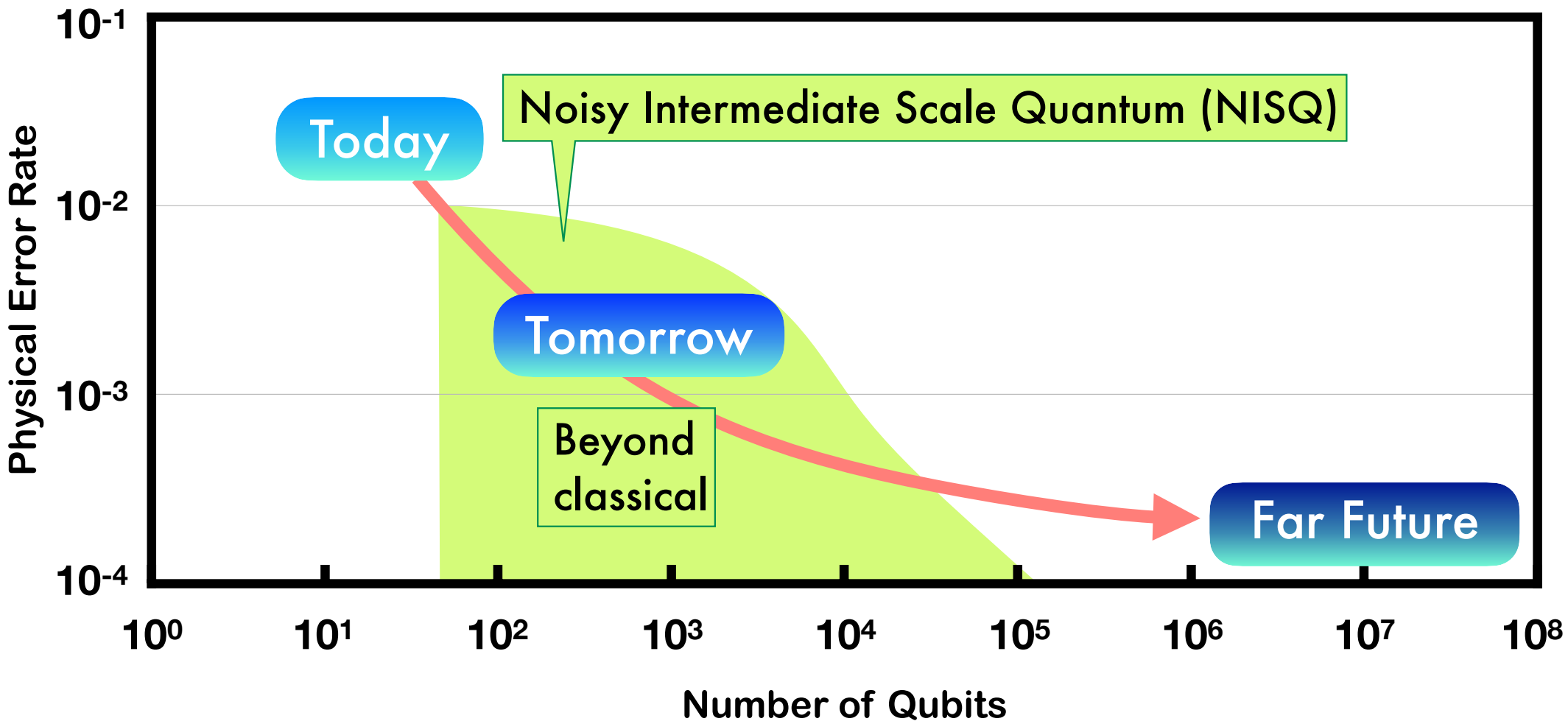


# Quantum computers are hard to build

- Qubits, unlike classical bits, need to interact strongly among themselves to form entangled states, which in turn form the basis for computation in quantum computers. But to achieve this experimentally is incredibly hard.



# Quantum Hardware Roadmap



# Is there a “Moore's law” for quantum computing?

- <https://arxiv.org/pdf/2303.15547>

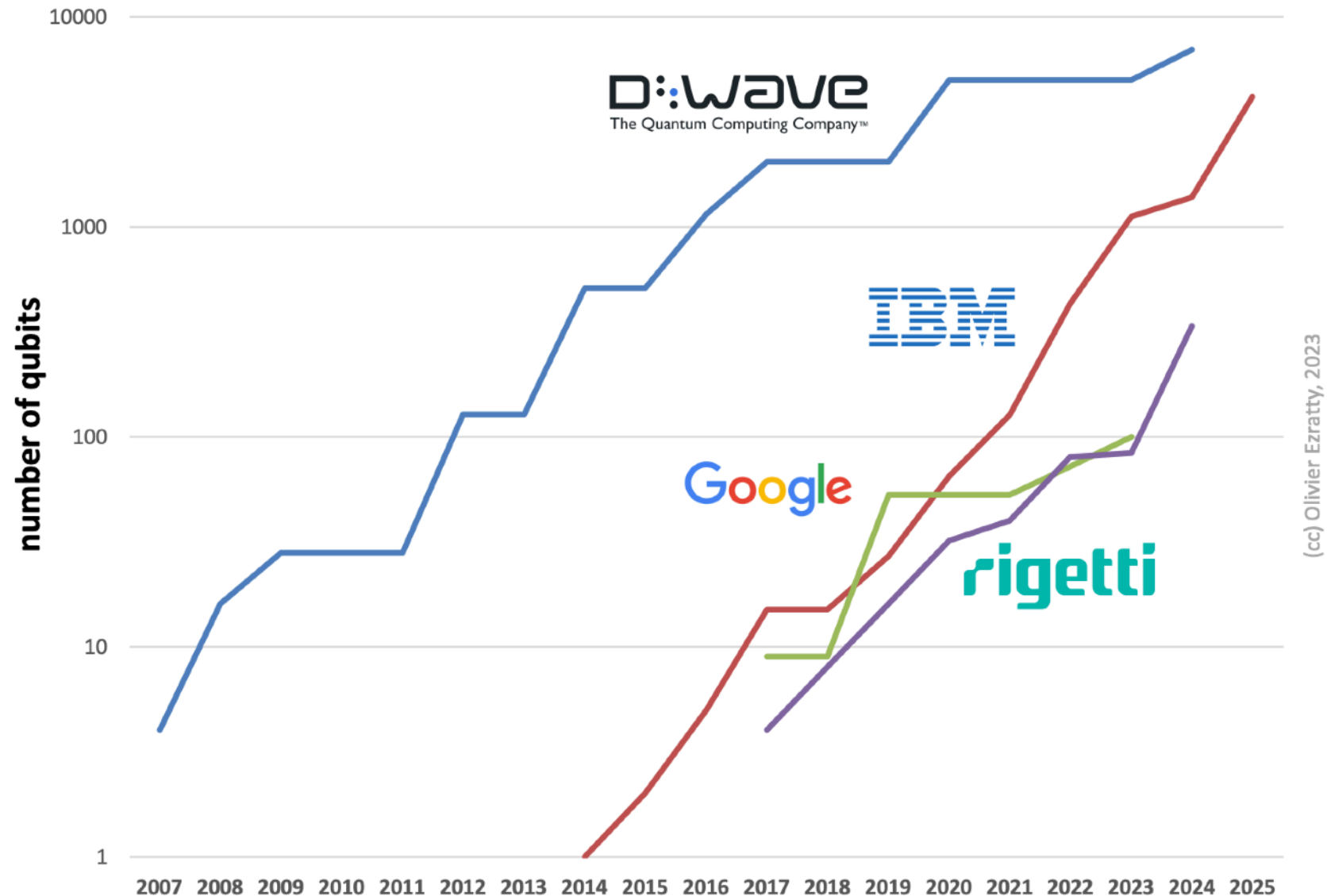


Figure 6: evolution of the number of physical qubits with D-Wave, IBM, Google and Rigetti. Compilation: Olivier Ezratty.

# Is there a “Moore's law” for quantum computing?

- <https://arxiv.org/pdf/2303.15547>

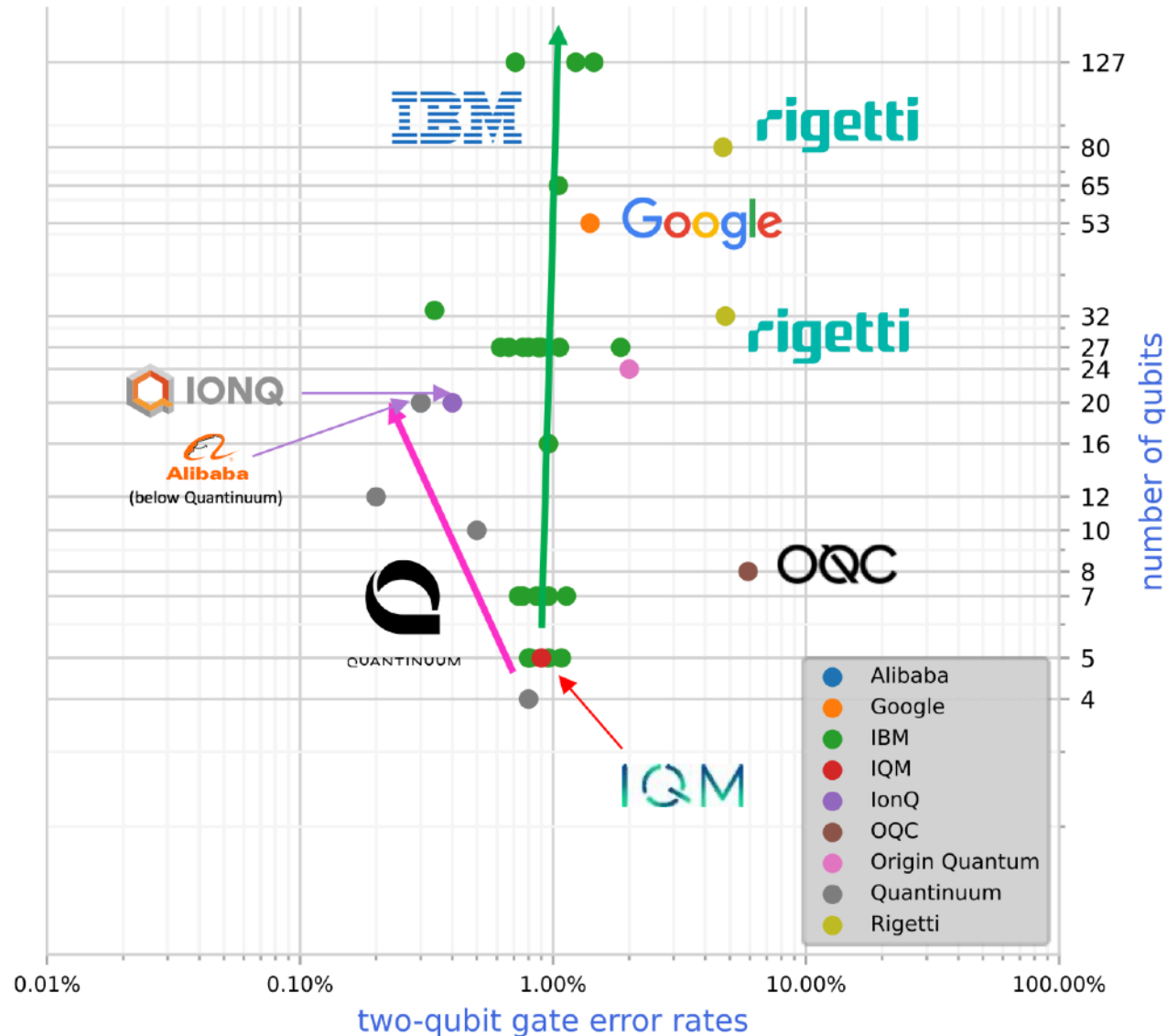


Figure 9: scatter plot of qubit numbers and two-qubit gate error rates for commercial vendors. Source: vendor fidelities numbers compiled by Olivier Ezratty as of March 2023.



| Willow System Metrics |                         |
|-----------------------|-------------------------|
| Number of qubits      | 105                     |
| Average connectivity  | 3.47<br>(4-way typical) |

| Quantum Error Correction (Chip 1)                            |                                                                             | Random Circuit Sampling (Chip 2)                             |                                                                             |
|--------------------------------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------|-----------------------------------------------------------------------------|
| Single-qubit gate error <sup>1</sup><br>(mean, simultaneous) | 0.035% ± 0.029%                                                             | Single-qubit gate error <sup>1</sup><br>(mean, simultaneous) | 0.036% ± 0.013%                                                             |
| Two-qubit gate error <sup>1</sup><br>(mean, simultaneous)    | 0.33% ± 0.18%<br>(CZ)                                                       | Two-qubit gate error <sup>1</sup><br>(mean, simultaneous)    | 0.14% ± 0.052%<br>(iswap-like)                                              |
| Measurement error<br>(mean, simultaneous)                    | 0.77% ± 0.21%<br>(repetitive, measure qubits)                               | Measurement error<br>(mean, simultaneous)                    | 0.67% ± 0.51%<br>(terminal, all qubits)                                     |
| Reset options                                                | Multi-level reset ( 1> state and above)<br>Leakage removal ( 2> state only) | Reset options                                                | Multi-level reset ( 1> state and above)<br>Leakage removal ( 2> state only) |
| T <sub>1</sub> time<br>(mean)                                | 68 μs ± 13 μs <sup>2</sup>                                                  | T <sub>1</sub> time<br>(mean)                                | 98 μs ± 32 μs <sup>2</sup>                                                  |
| Error correction cycles<br>per second                        | 909,000<br>(surface code cycle = 1.1 μs)                                    | Circuit repetitions per second                               | 63,000                                                                      |
| Application performance                                      | Λ <sub>3,5,7</sub> = 2.14 ± 0.02                                            | Application performance                                      | XEB fidelity depth 40 = 0.1%                                                |
|                                                              |                                                                             | Estimated time on Willow<br>vs classical supercomputer       | 5 minutes vs. 10 <sup>25</sup> years                                        |

# Breaking limitation of quantum annealer in solving optimization problems under constraints

Masayuki Ohzeki<sup>1,2,3\*</sup>

2002.05298

[\*Nature, Scientific Reports\* volume 10, Article number: 3126 \(2020\)](#)

Quantum annealing is a generic solver for optimization problems that uses fictitious quantum fluctuation. The most ground-breaking progress in the research field of quantum annealing is its hardware implementation, i.e., the so-called quantum annealer, using artificial spins. However, the connectivity between the artificial spins is sparse and limited on a special network known as the chimera graph. Several embedding techniques have been proposed, but the number of logical spins, which represents the optimization problems to be solved, is drastically reduced. In particular, an optimization problem including fully or even partly connected spins suffers from low embeddable size on the chimera graph. In the present study, we propose an alternative approach to solve a large-scale optimization problem on the chimera graph via a well-known method in statistical mechanics called the Hubbard-Stratonovich transformation or its variants. The proposed method can be used to deal with a fully connected Ising model without embedding on the chimera graph and leads to nontrivial results of the optimization problem. We tested the proposed method with a number of partition problems involving solving linear equations and the traffic flow optimization problem in Sendai and Kyoto cities in Japan.

Supply chain logistics

Route Optimization

Portfolio management

Nurse scheduling problem

Image recognition

Remote sensing imagery

Classifier optimization

Drug discovery

Material science

Seismic inversion

Quantum simulation

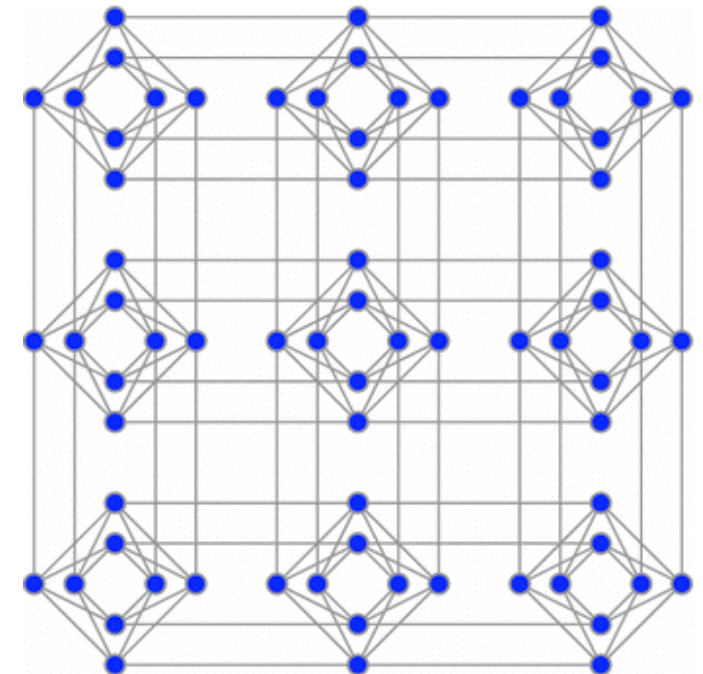
Financial modeling

Cryptography

Better batteries

Cleaner fertilization

Electronic material discovery

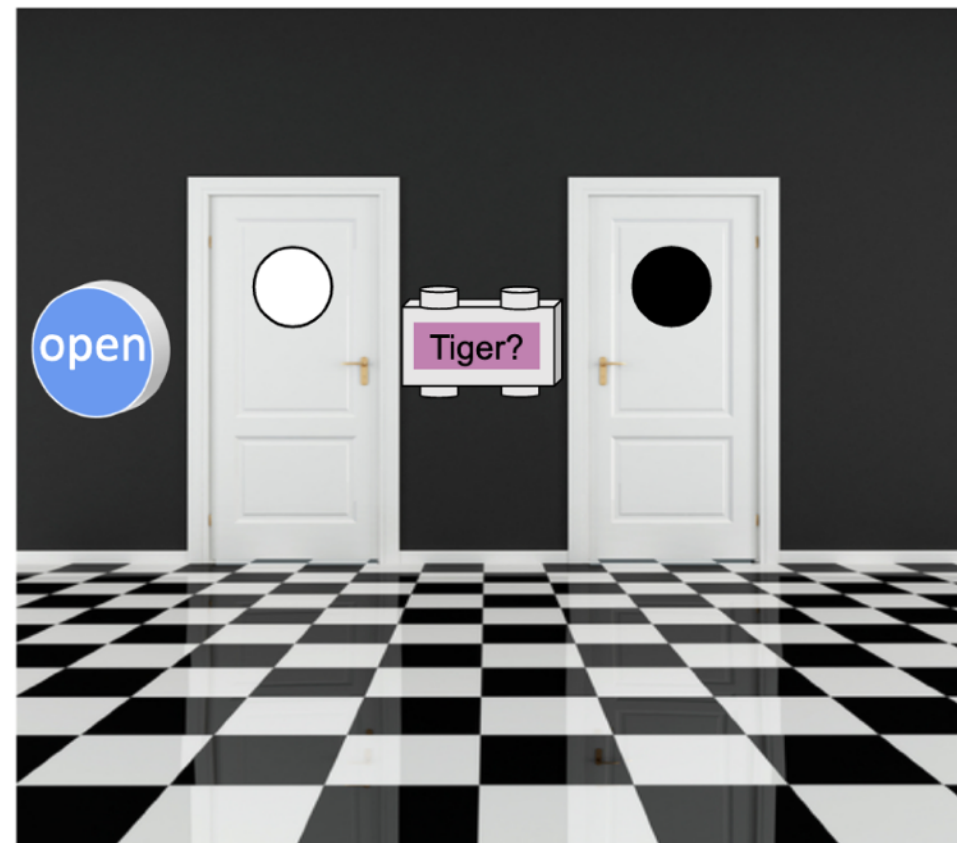


# \$ vs Tiger

- Teaching quantum information science to high-school and early undergraduate students by Sophia Economou, Terry Rudolph, Edwin Barnes, 2005.07874
- You encounter two doors:  
Money behind at least one door



- Tiger might be lurking behind one door



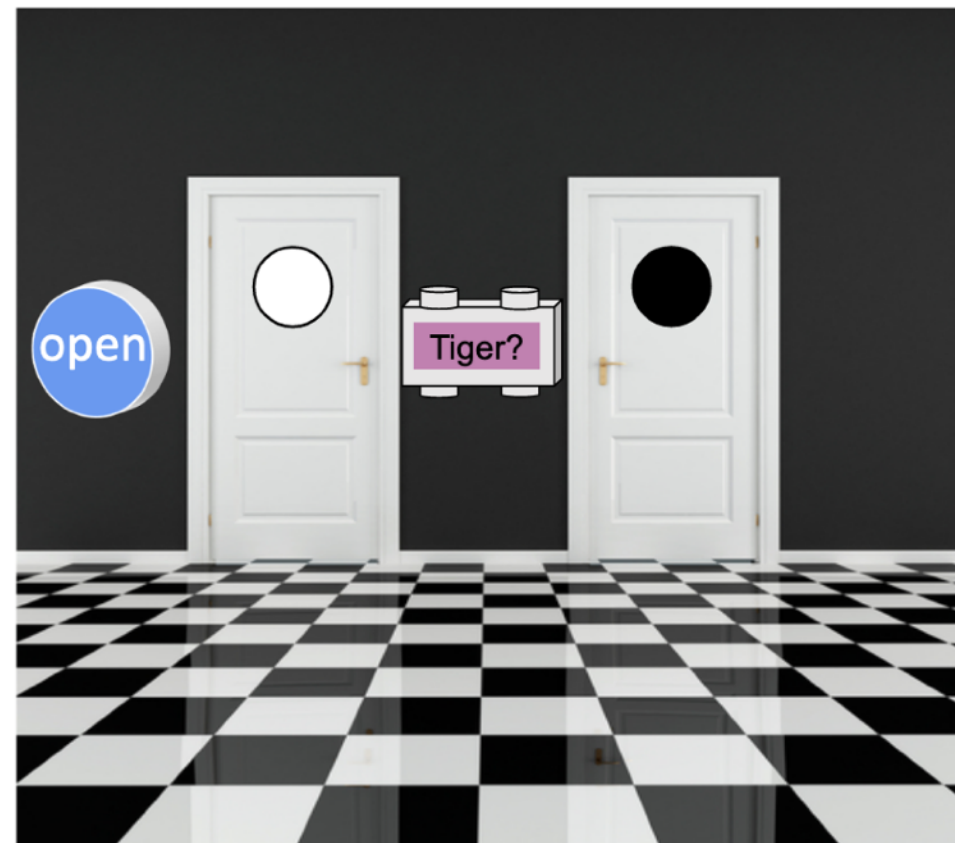






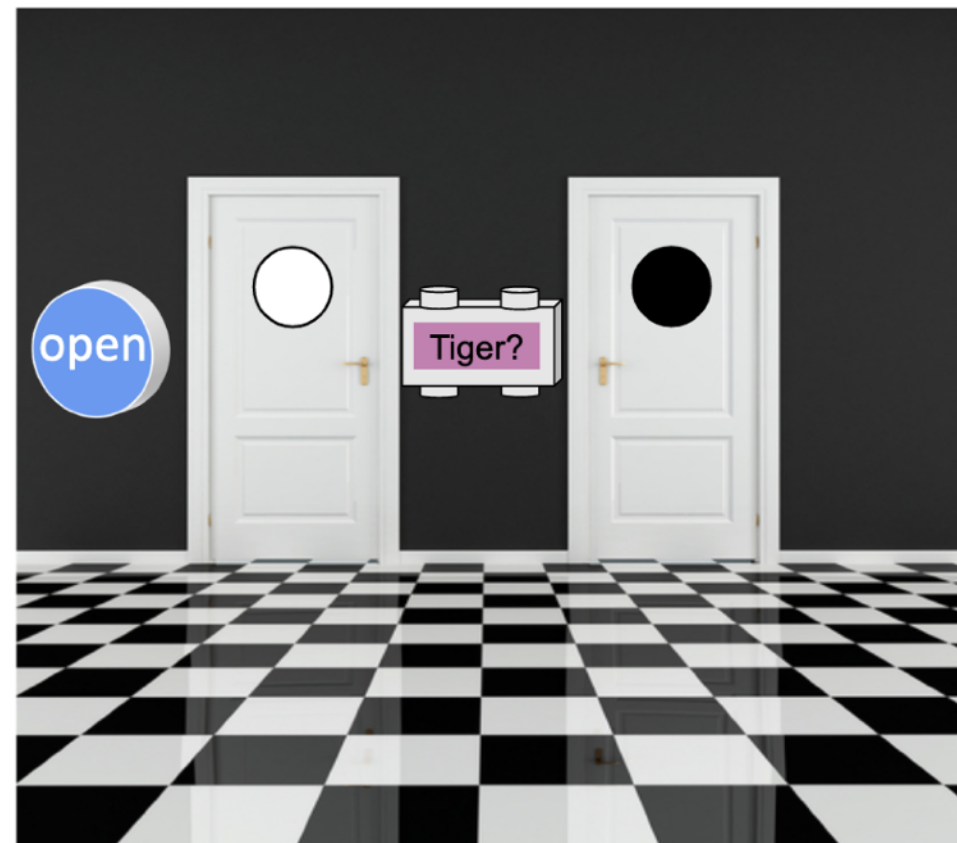
# \$ vs Tiger

- The button on the left opens both doors
- YOU WANT TO BE SURE THERE'S NO TIGER BEHIND EITHER DOOR BEFORE YOU PUSH THE "OPEN" BUTTON
- The device in the middle will tell you if there is a tiger behind the door that you ask about – but you only get to use it once



# \$ vs Tiger

- List the three different scenarios for what's behind the doors:



# \$ vs Tiger

- List the three different scenarios for what's behind the doors:



# \$ vs Tiger

- Make a truth table for the tiger box for each of the scenarios



|         | In | Out |
|---------|----|-----|
| Door 0  |    |     |
| Open? 1 |    |     |
| Door 1  |    |     |
| Open? 1 |    |     |

|         | In | Out |
|---------|----|-----|
| Door 0  |    |     |
| Open? 1 |    |     |
| Door 1  |    |     |
| Open? 1 |    |     |

|         | In | Out |
|---------|----|-----|
| Door 0  |    |     |
| Open? 1 |    |     |
| Door 1  |    |     |
| Open? 1 |    |     |



# \$ vs Tiger

- Make a truth table for the tiger box for each of the scenarios



|         | In | Out |
|---------|----|-----|
| Door 0  | 0  | 0   |
| Open? 1 | 1  | 1   |
| Door 1  | 1  | 1   |
| Open? 1 | 1  | 0   |

|         | In | Out |
|---------|----|-----|
| Door 0  | 0  | 0   |
| Open? 1 | 1  | 1   |
| Door 1  | 1  | 1   |
| Open? 1 | 1  | 1   |

|         | In | Out |
|---------|----|-----|
| Door 0  | 0  | 0   |
| Open? 1 | 1  | 0   |
| Door 1  | 1  | 1   |
| Open? 1 | 1  | 1   |

1 = no tiger  
0 = tiger

# \$ vs Tiger

- What gate(s) correspond to the truth table for each scenario?

Door 1

Tiger?

Door 1

1 = no tiger,  
0 = tiger



|         | In | Out |
|---------|----|-----|
| Door 0  | 0  | 0   |
| Open? 1 | 1  | 1   |
| Door 1  | 1  | 1   |
| Open? 1 | 1  | 0   |



|         | In | Out |
|---------|----|-----|
| Door 0  | 0  | 0   |
| Open? 1 | 1  | 1   |
| Door 1  | 1  | 1   |
| Open? 1 | 1  | 1   |



|         | In | Out |
|---------|----|-----|
| Door 0  | 0  | 0   |
| Open? 1 | 1  | 0   |
| Door 1  | 1  | 1   |
| Open? 1 | 1  | 1   |

1 = no tiger  
0 = tiger

# \$ vs Tiger

- What gate(s) correspond to the truth table for each scenario?

Door 1

Tiger?

Door 1 = no tiger,  
0 = tiger





1 = no tiger  
0 = tiger

|        | In | Out |
|--------|----|-----|
| Door 0 | 0  | 0   |
| Open?  | 1  | 1   |
| Door 1 | 1  | 1   |
| Open?  | 1  | 0   |

Conditional NOT



|        | In | Out |
|--------|----|-----|
| Door 0 | 0  | 0   |
| Open?  | 1  | 1   |
| Door 1 | 1  | 1   |
| Open?  | 1  | 1   |

Identity



|        | In | Out |
|--------|----|-----|
| Door 0 | 0  | 0   |
| Open?  | 1  | 0   |
| Door 1 | 1  | 1   |
| Open?  | 1  | 1   |

Both are possible.

|        | In | Out |
|--------|----|-----|
| Door 0 | 0  | 0   |
| Open?  | 1  | 0   |
| Door 1 | 1  | 1   |
| Open?  | 1  | 1   |

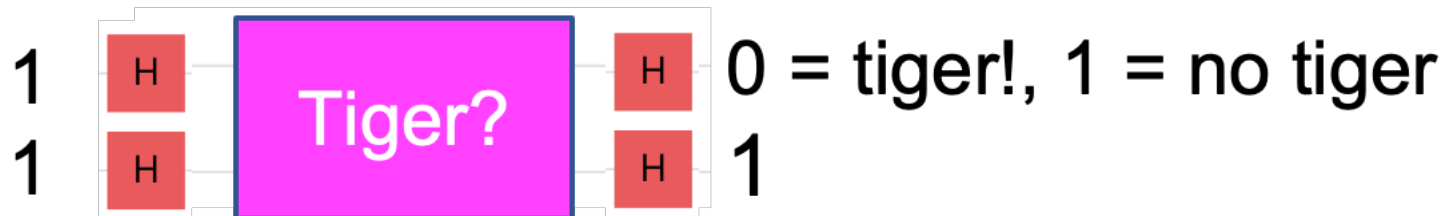
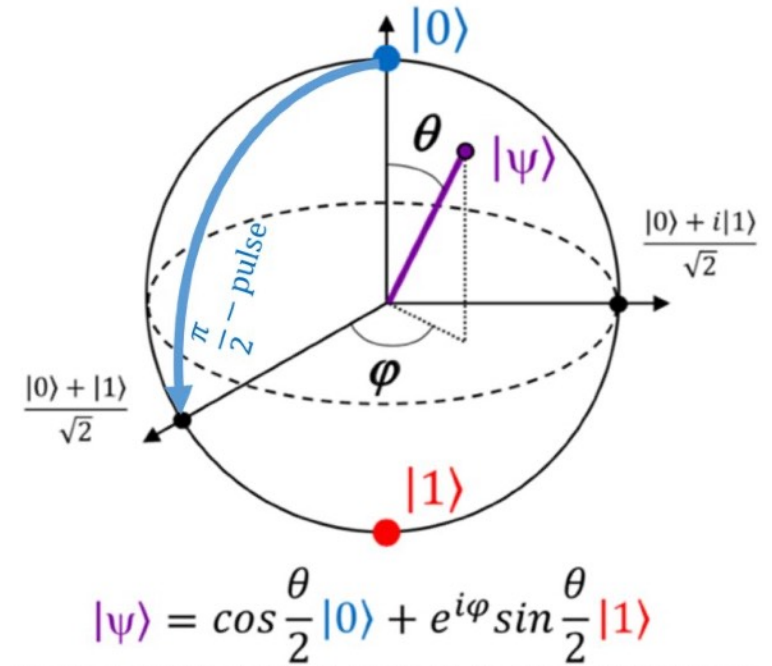
# \$ vs Tiger

- Challenge: We can't change the tiger box, but can we add gates before and/or after it such that we can determine if there is a tiger somewhere by ONLY USING THE TIGER BOX ONCE?
- We're trying to prove that quantum computing let's us do things that are impossible with classical computing. Therefore, consider adding some quantum gates.
- Hint 1: We'd like to query both doors with one push of a button, so maybe we should put the "Door" bit into a **superposition**.
- Hint 2: We definitely don't want a superposition output, so we maybe we should add a second H to the "Door" bit.
- Hint 3: Our inputs will always be 11 for the solution.
- Hint 4: We want the output to be 11 for no tiger and 10 for tiger.



# \$ vs Tiger

- H changes 0 into + state.
- H changes 1 into - state.



# \$ vs Tiger



| In |   | Out |   |
|----|---|-----|---|
| 1  | H | H   | 0 |
| 1  | H | H   | 1 |

| In |   | Out |   |
|----|---|-----|---|
| 1  | H | H   | 1 |
| 1  | H | H   | 1 |

| In |   | Out |   |
|----|---|-----|---|
| 1  | H | H   | 0 |
| 1  | H | H   | 1 |

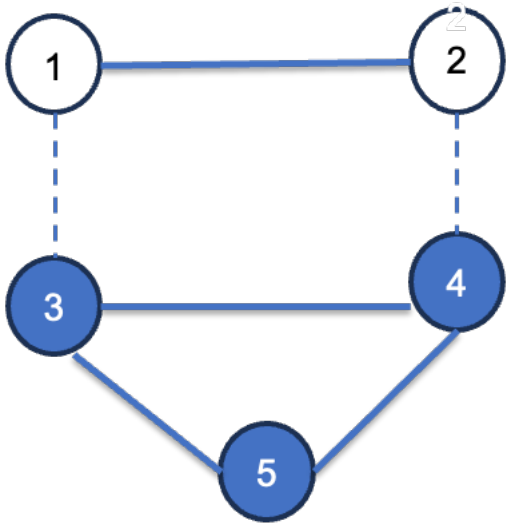
- What does this tell us?
  - We can solve (some) unsolvable problems with quantum computing
  - We can determine IF there is a tiger, but not WHICH DOOR

# Quantum Optimization

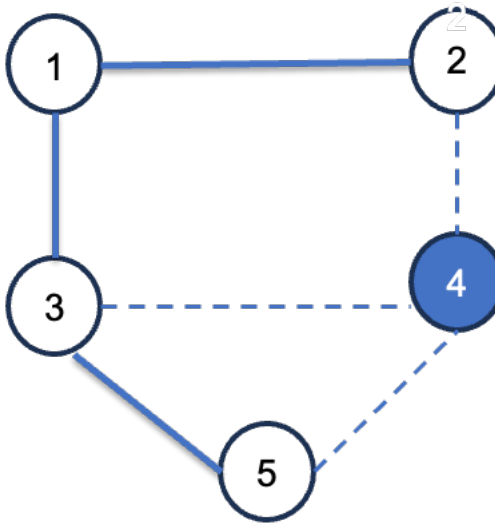
- Optimization problems are everywhere.
  - Continuous optimization
  - Discrete optimization: combinatorial optimization
  - Quadratic Unconstrained Binary Optimization (QUBO)
    - NP hard problem
    - Quadratic function might have several local minima
    - Close connection to Ising model
- Apply quantum algorithms to solve optimization problem
  - Gate model: use universal gates (Pauli's)
  - Non-gate model (quantum annealer): relies on adiabatic theorem to find a minimum energy of Hamiltonian corresponding to the minimum value of some cost function.

# MaxCut problem

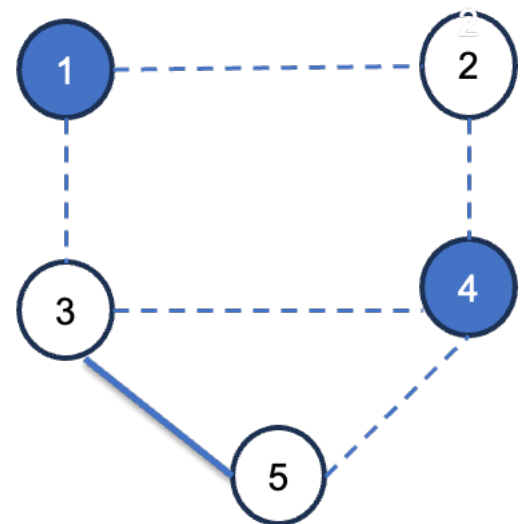
- Objective:
  - Maximize the number of cut edges in a graph when split into 2 parts
  - Divides the set of nodes in the graph into two subsets so that we have as many edges as possible that go between the two sets



Cut size = 2



Cut size = 3

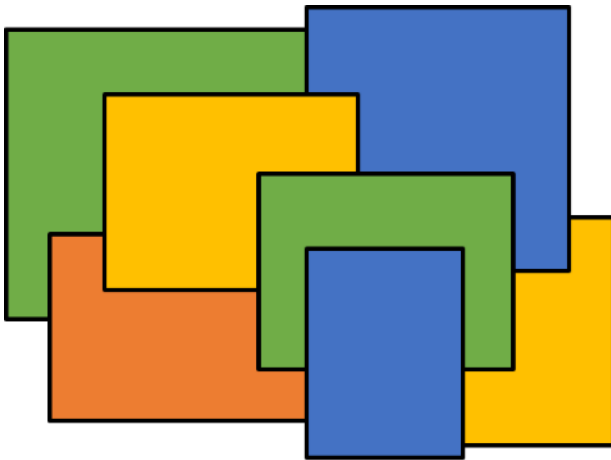


Cut size = 5

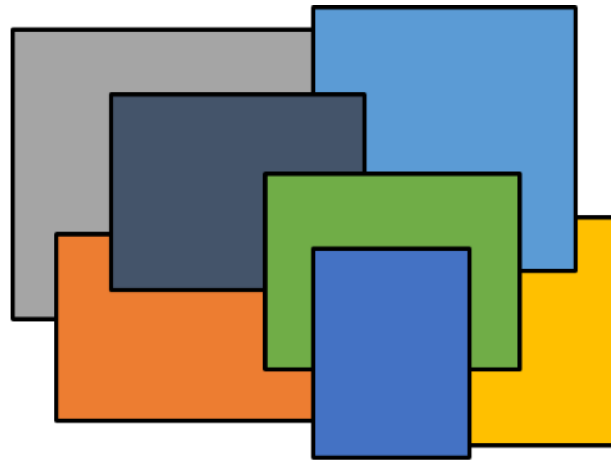


# Map Coloring

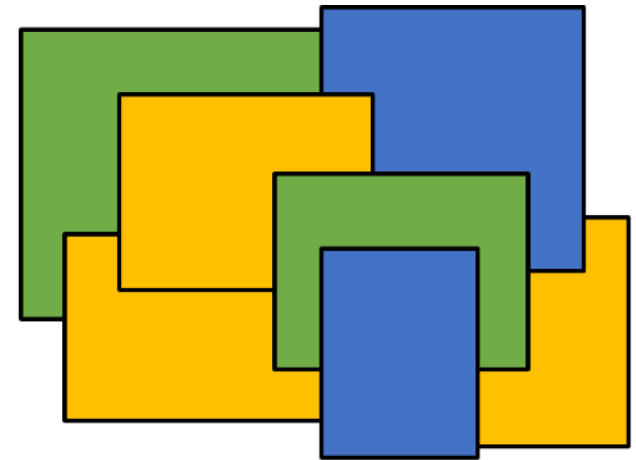
- Problem: Color the regions of a given map such that
  - at most four colors are used
  - no two adjacent\* regions have the same color



Valid four-coloring



Invalid; more than 4 colors

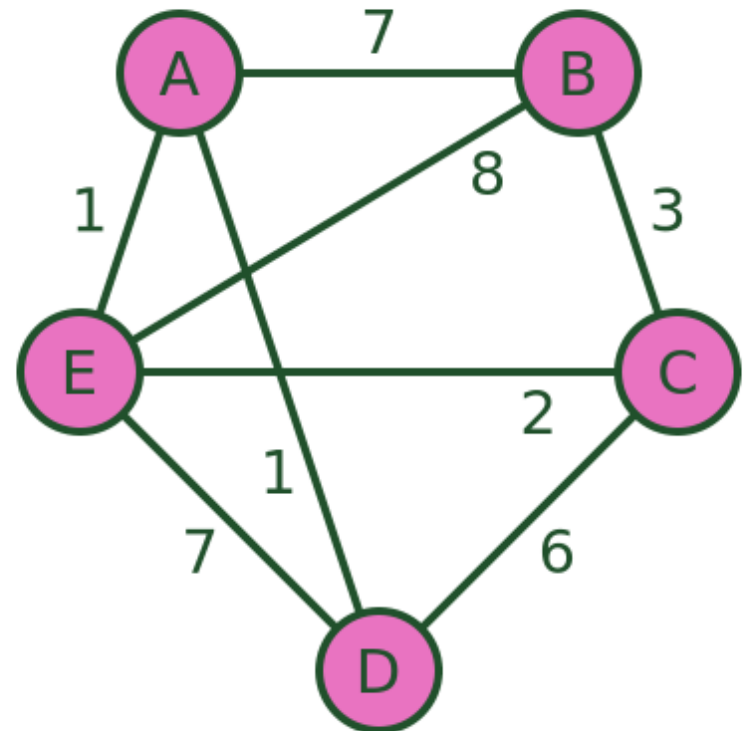


Invalid; yellows touch

\* "adjacent" means "shares an edge"; sharing a corner is OK

# Traveling salesman problem (TSP)

- Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?
- It is an NP-hard problem in combinatorial optimization, important in theoretical computer science and operations research.



# Traveling salesman problem (TSP)

- Performance of the Bellman–Held–Karp algorithm
- Time Complexity
  - The Bellman-Held-Karp algorithm has a time complexity of  $\mathcal{O}(n^2 2^n)$ , where  $n$  is the number of cities.
  - This means the runtime increases exponentially with the number of cities, making it impractical for very large instances of the TSP.
  - However, this is still significantly better than the brute-force approach that has a time complexity of  $\mathcal{O}(n!)$ , where ' $n$ ' is the number of cities.
- Space Complexity
  - The algorithm has a space complexity of  $\mathcal{O}(n 2^n)$ .
  - This is due to the algorithm needing to store intermediate results in a table, especially for storing the shortest path costs for all possible subsets of cities and destination cities.
  - This space requirement can become a limiting factor for larger problems as well.
- Query complexity of QAOA on TSP:  $\mathcal{O}(\sqrt{n!})$ .  $(n^2 2^n \gg \sqrt{n!} \text{ for a large } n)$ 
  - Challenges
    - Implementing QAOA on real quantum hardware
    - Optimization of Parameters:

# Traveling salesman problem (TSP)

- Label vertices  $1, \dots, N$  and the edge set  $(uv)$  to be directed. (For undirected, add  $(uv)$  and  $(vu)$ ).
- Introduce  $N^2$  bits  $x_{v,i}$ , where  $v$  represents the vertex and  $i$  represents its order to the edge set.
- Every vertex can only appear once in a cycle, and that there must be a  $j$ -th node in the cycle for each  $j$ .
- For the nodes in our prospective ordering, if  $x_{u,j}$  and  $x_{u,j+1}$  are both 1, then there should be an energy penalty if  $(uv) \notin E$ .

$$H_A = A \sum_{v=1}^n \left( 1 - \sum_{j=1}^N x_{v,j} \right)^2 + A \sum_{j=1}^n \left( 1 - \sum_{v=1}^N x_{v,j} \right)^2 + A \sum_{(uv) \notin E} \sum_{j=1}^N x_{u,j} x_{v,j+1}$$

- $A > 0$  is a constant. The ground state of this system has  $H = 0$ , only if we have an ordering of vertices where each vertex is only included once, and adjacent vertices in the cycle have edges on the graph – i.e., we have a **Hamiltonian cycle**.

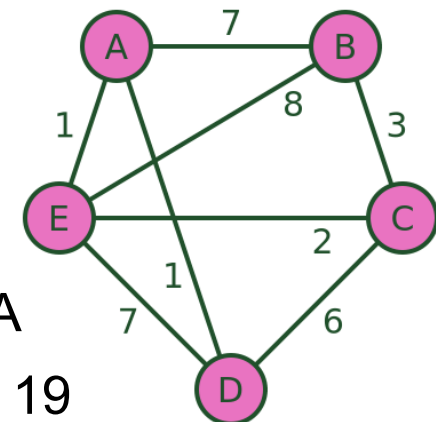
- The traveling salesman also needs to minimize the total traveling distance (weight)

$$H_B = B \sum_{(uv) \in E} W_{uv} \sum_{j=1}^N x_{u,j} x_{v,j+1}$$

- $B$  should be small enough that it is never favorable to violate the constraints of  $H_A$ .  $0 < B \max(W_{uv}) < A$

$$H_{\text{full}} = H_P = H_A + H_B$$

|   | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| A | 1 |   |   |   |   |
| B |   |   | 1 |   |   |
| C |   |   |   | 1 |   |
| D |   |   |   |   |   |
| E |   | 1 |   |   | 1 |



AEBCDA

$$1+8+3+6+1 = 19$$



## Portfolio optimization

Markowitz model

$$F = \sum_{ij} C_{ij} n_i n_j - \zeta \sum_i R_i n_i$$

risk minus returns

no. of assets of type-i

risk tolerance

correlations between assets

return on i'th asset

## Spin glasses

Sherrington-Kirkpatrick model

$$H = \sum_{ij} J_{ij} s_i s_j + \sum_i h_i s_i$$

Hamiltonian

spin at site i

couplings between sites

external magnetic field at i'th site

## Neural networks

Hopfield model

$$E = \sum_{ij} w_{ij} v_i v_j + \sum_i \theta_i v_i$$

energy function

state of neuron i

weights of the learning rule

activation threshold for i'th neuron

# Quadratic Unconstrained Binary Optimization (QUBO)

- QUBO: combinatorial optimization problem with a wide range of applications from finance to ML (partitioning, graph coloring, task allocation, max-sat, max-cut etc)

$$f: \mathbb{Z}_2^n \longrightarrow \mathbb{R}$$

Quadratic polynomial over binary variable

$$f(x) = \sum_{i=1}^n \sum_{j=1}^i q_{ij} x_i x_j + \sum_{i=1}^n h_i x_i$$

$$x_i \in \mathbb{Z}_2 = \{0,1\}, \quad h_i, q_{ij} \in \mathbb{R}$$

$$x = (x_n x_{n-1} \cdots x_2 x_1)$$

- Find a binary vector  $x^*$  which minimizes  $f$  (binary strings of n-bits)

$$x^* = \underset{x \in \mathbb{Z}_2^n}{\operatorname{argmin}} f(x)$$

- In matrix notation,  $f(x) = x^T Q x$ , where  $Q \in \mathbb{R}^{n \times n}$
- NP-hard problem: no polynomial-time algorithms are known.

# Ising formulations of many NP problems

## 1 Introduction

- 1.1 Quantum Adiabatic Optimization . . . . .
- 1.2 Ising Spin Glasses . . . . .
- 1.3 The Goal of This Paper . . . . .
- 1.4 What Problems Are Easy (to Embed) on Experimental AQO Devices? . .

Andrew Lucas  
1302.5843

## 2 Partitioning Problems

- 2.1 Number Partitioning . . . . .
- 2.2 Graph Partitioning . . . . .
- 2.3 Cliques . . . . .
- 2.4 Reducing  $N$  to  $\log N$  Spins in Some Constraints . . . . .

$$H = - \sum_{i,j} J_{ij} \sigma_i^z \sigma_j^z - \sum_i h_i \sigma_i^z$$

## 3 Binary Integer Linear Programming

## 4 Covering and Packing Problems

- 4.1 Exact Cover . . . . .
- 4.2 Set Packing . . . . .
- 4.3 Vertex Cover . . . . .
- 4.4 Satisfiability . . . . .
- 4.5 Minimal Maximal Matching . . . . .

## 5 Problems with Inequalities

- 5.1 Set Cover . . . . .
- 5.2 Knapsack with Integer Weights . . . . .

## 6 Coloring Problems

- 6.1 Graph Coloring . . . . .
- 6.2 Clique Cover . . . . .
- 6.3 Job Sequencing with Integer Lengths . . . . .

## 7 Hamiltonian Cycles

- 7.1 Hamiltonian Cycles and Paths . . . . .
- 7.2 Traveling Salesman . . . . .

## 8 Tree Problems

- 8.1 Minimal Spanning Tree with a Maximal Degree Constraint . .
- 8.2 Steiner Trees . . . . .
- 8.3 Directed Feedback Vertex Set . . . . .
- 8.4 Undirected Feedback Vertex Set . . . . .
- 8.5 Feedback Edge Set . . . . .

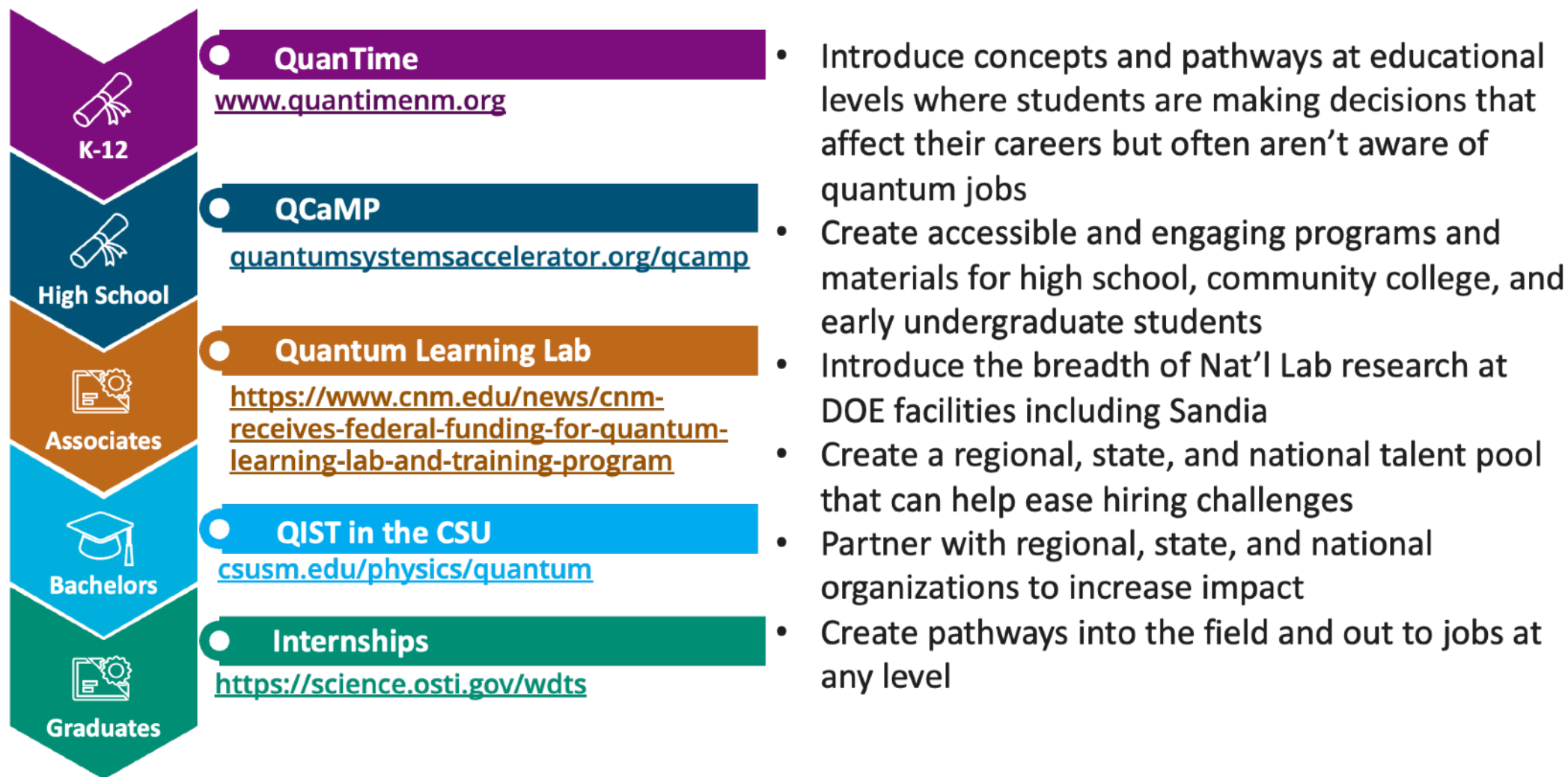
## 9 Graph Isomorphisms

## 10 Conclusions

- Many schools and internship opportunities for graduate, **undergraduate and high school students!**
- REU program
- Workshops and conferences
- Involvement with National labs and government agencies
  - NASA, DoD, DOE, NSF, many private foundations



# QUANTUM WORKFORCE DEVELOPMENT AT SANDIA





# Quantum, Computing, Mathematics, & Physics Summer Camp

## WHAT IS QCaMP?

- Two summer camps introducing high school teachers and students to quantum concepts and careers



## 2025 Camps

**Teachers: June 16-July 18, 2025**

**Students: June 30-July 25, 2025**

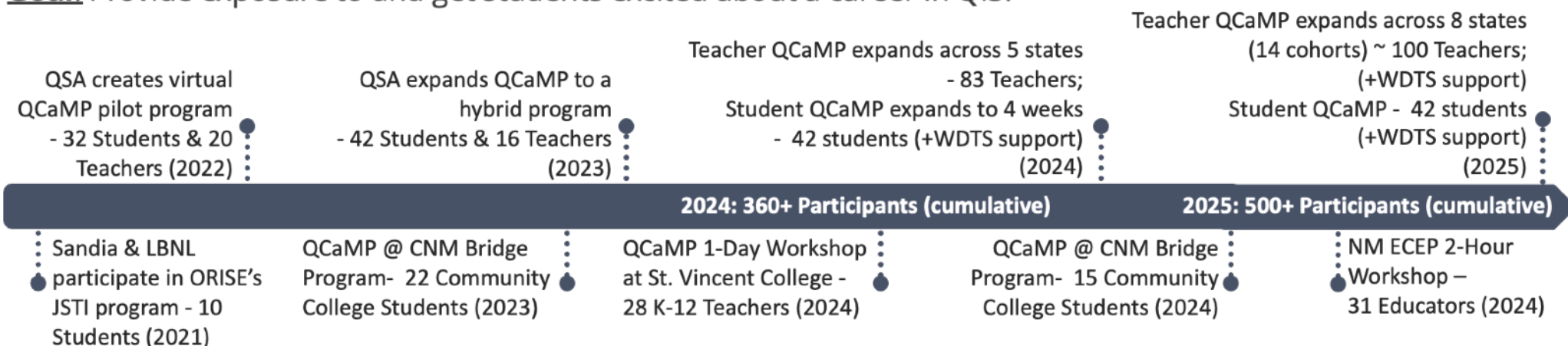
[sandia.gov/quantum/qcamp/](https://sandia.gov/quantum/qcamp/)

## QCaMP GOALS AND GUIDING PRINCIPLES

**Goal:** Reduce barriers. Stipends for all. No prerequisites! Hands-on puzzles/experiments throughout.

**Goal:** Give teachers tools to introduce quantum topics to their students, allowing us to **reach more students**.

**Goal:** Provide exposure to and get students excited about a career in QIS.



203 educators and 163 students reached since program inception!

Taken from Megan Ivory's presentation at QIST workshop 2025



# NASA Quantum Artificial Intelligence Laboratory (QuAIL)

*QuAIL is the space agency's hub for assessing and advancing the potential of quantum computers to impact computational challenges faced by the agency in the decades to come.*

## Overview

Quantum computing is an emerging computational paradigm with the potential to revolutionize diverse areas of future-generation computational systems. QuAIL's mandate is to determine and advance the potential for quantum computation to enable more ambitious, efficient, and safer NASA missions in the future. The team focuses on hard computational problems whose solution would impact NASA's aeronautics, Earth and space sciences, and space exploration missions.

The QuAIL team tracks and contributes to advances in algorithms, both near-and longer-term, for optimization, machine learning, simulation of condensed-matter, high-energy physics, chemistry and materials, and differential equations and computational fluid dynamics. While the group is a theory and numerical team, a key component of this work is close collaboration with quantum hardware groups. Hardware-algorithm co-design is central to the team's work, with algorithmic needs feeding into the hardware design and prioritization of hardware capabilities, hardware limitations feeding into algorithm design, and hardware noise characterization feeding into the design of protocols for error mitigation and correction. Key to this research has been advancing tools, including classical circuit simulation and open quantum system modeling, leading to an improved understanding of co-design principles across multiple architectures, including gate-model, adiabatic, and measurement-based architectures.





Home : [Our Work](#) : [Areas of Research](#) : [Quantum Research](#)

## Quantum Research

Email: [nrlpao@nrl.navy.mil](mailto:nrlpao@nrl.navy.mil)

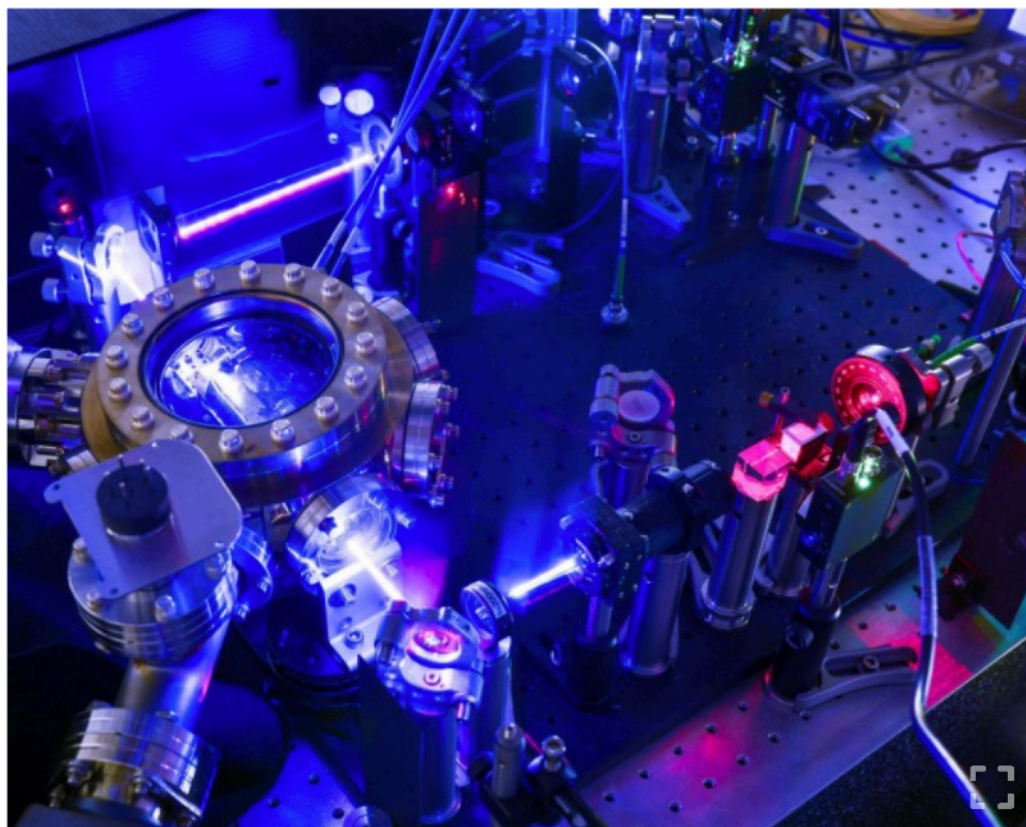
### History

The beginning of research into Quantum Information Science (QIS) can be traced to theoretical physicist, Richard Feynman, Ph.D. In 1982 he proposed that computers that take advantage of quantum mechanical principles may have certain advantages over classical computers. Since then, researchers have proposed or demonstrated various methods of using quantum information to achieve results that cannot be obtained with classical physics. One of the most striking proposals is the quantum computer itself.



# Army designates Quantum Information Science Research Center

By U.S. Army DEVCOM Army Research Laboratory Office of Strategic Communications July 5, 2023



## TOP STORIES

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JANUARY 20, 2025

**National Guard Bureau leaders meet with Guardsmen supporting 60th Presidential Inauguration**

JANUARY 17, 2025

**42nd Infantry Division heads to Warfighter exercise**

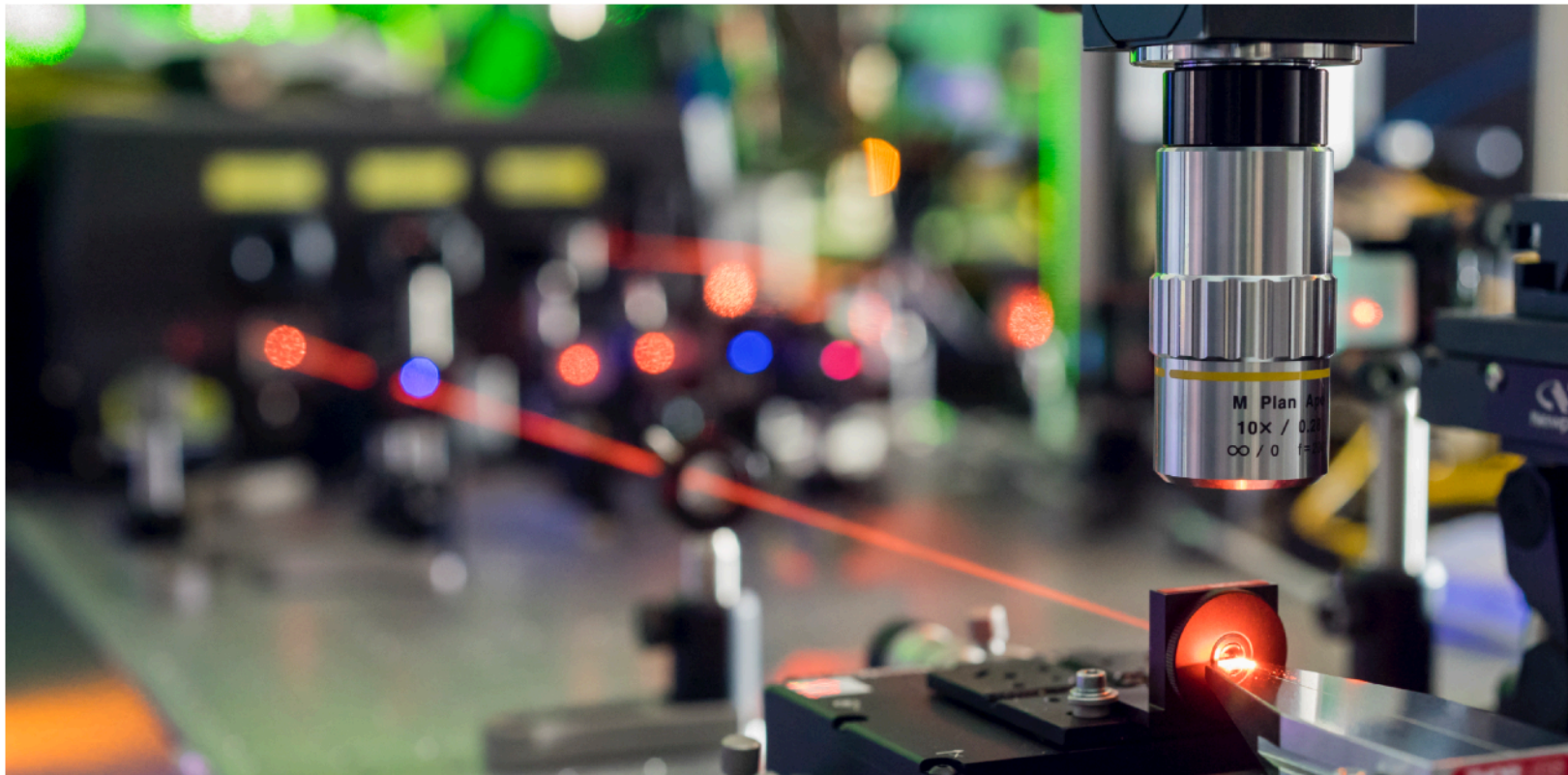
JANUARY 16, 2025

**Bradley improvement tested at US Army Yuma Proving Ground**

JANUARY 1, 2025

**Army provides Soldiers, Families variety**

## AFRL – Quantum Information Science & Technology



### AFRL/RITQ - Quantum Networking and Computing

- Integrated Photonics and Photon Qubits
- Quantum Algorithms
- Superconducting and Hybrid Quantum Systems
- Trapped Ions

### Contact Information:

Email: [ri.quantum.gov@afrl.af.mil](mailto:ri.quantum.gov@afrl.af.mil)

# Quantum Ideas Summer School

The Quantum Ideas Summer School is open to Undergraduates, Graduate Students, and Industry participants. Support for Undergraduate and Graduate students is funded by the National Science Foundation (award #PHY-1818914).

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## 2024 Session

### Lecture Notes (Session Recordings coming soon)

Day 1 | Quantum Information Basics

- [Part 1: Quantum Information Basics - Aram Harrow](#)
- [Part 1 Session recording](#)
- [Part 2: Quantum Information Basics- Akimasa Miyake](#)
- [Part 2 Session recording](#)

Day 2 | Neutral Atom Quantum Computing + Quantum Simulation of Everything

- [Part 1: Neutral Atom Quantum Computing - Jacob Covey](#)
- [Part 1 Session recording](#)
- [Part 2: Quantum Simulation of Everything - Peter Love](#)

Undergraduate and Graduate student support is funded by the National Science Foundation (award #PHY-1818914) and outlined in [Participant Travel Guidelines](#).

For more details, contact the [STAQ Administrator](#).

## 2023 Session

### Lecture Notes and Session Recordings

[Day 1 | Quantum Information Basics](#)

[Day 2 | Ions and QECC](#)

(Day 3 - Offsite programming. No lectures)

[Day 4 | Superconductors and Algorithms](#)

[Day 5 | Quantum Architecture and Optimization](#)

## 2022 Session

Duke  
Since 2019

For undergraduate and graduate students



## Undergraduate Quantum Summer School

Aug 14 and 15, 2024 Northwestern University

Not sure whether  
there will be a  
school in 2025



<https://forms.gle/BaNkcoRL3ozeQPit8>

### What to expect:

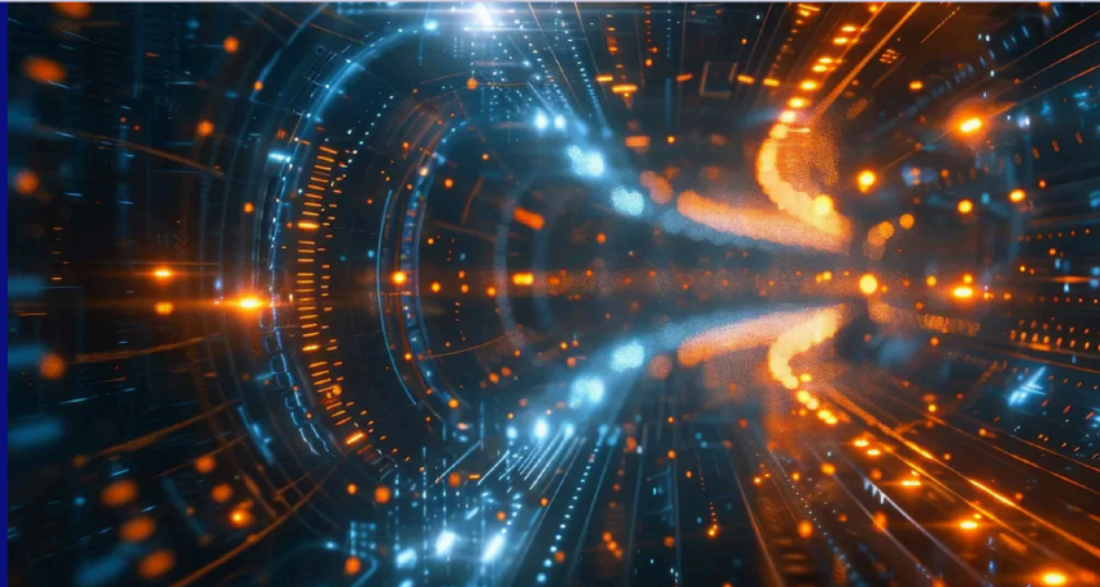
The IQ-PARC project, funded by the Defense Department's National Defense Education Program, is extending an invitation to underrepresented students from Illinois and nationwide to participate in a workshop focused on Quantum technologies, to be held at Northwestern University. Recognizing the importance of diversity in the advancement of these critical technological fields, the project aims to foster an inclusive environment that encourages participation from all corners of the academic community. Successful applicants will receive a stipend of \$1,000, in reimbursement, to cover travel and lodging expenses in Evanston, IL, ensuring that financial barriers do not hinder the opportunity to engage in this transformative educational experience. There will be presentations by faculty and industry partners introducing quantum technologies, cutting-edge research areas, and related job opportunities particularly in the areas of national security.

### Registration:

Application: Space is limited, up to 1000 USD will be available to selected participants. Please use the QR code, to apply by May 15, 2024. Decisions will be sent by June 15, 2024.



# Quantum Computing Summer School Fellowship



## Developing new leaders in the theory, application, and programming of quantum computers

For undergraduate and  
graduate students

**Applications are open until January 19th 2025**

The Quantum Computing Summer School is an immersive 10-week curriculum that includes tutorials from world-leading experts in quantum computation as well as one-on-one mentoring from LANL staff scientists who are conducting cutting-edge quantum computing research. Summer school fellowship recipients will be exposed to the theoretical foundations of quantum computation and will become skilled at programming commercial quantum computers, such as those developed by D-Wave Systems, Quera, Quantinuum, and IBM. Roughly twenty students (with the precise number determined based on the applicant pool) will be awarded a fellowship for the summer school. The fellowship amount ranges from \$10,000 to \$20,000, based on academic rank. All students (undergraduate and graduate) are encouraged to apply.

The school will be held from June 2nd to August 8th 2025.





ORNL

The 2025 **U.S. Quantum Information Science Summer School (USQIS)** will be hosted by the Quantum Science Accelerator at Lawrence Berkeley National Laboratory. Dates and application information TBA.



FNAL

For undergraduate and graduate students

## C<sup>2</sup>QA QIS 102: Applied Quantum Computing Summer School

June 10 – 28, 2024

*“There is a distinct need to teach students core scientific computing,  
and then stitch quantum computing concepts to enhance intuition and skills.”*

David Biersach  
Senior Technology Architect  
Brookhaven National Laboratory

Brookhaven National Laboratory offers a three-week virtual workshop to introduce rising college juniors, seniors, and recent college graduates to the exciting world of quantum information science (QIS). Led by **Dr. David Biersach**, through a series of demonstrations and hands-on programming labs, students will learn how quantum algorithms, when applied to specific problem domains, can outperform classical computers. Students will learn **IBM Qiskit**, a world-class software package for working with quantum computers at the level of pulses, circuits, and application modules. Students will download and install the 100% open-source courseware and development tools on their personal computers, which they will use during the program. Accepted students will be provided with a weekly stipend of \$500 and those who successfully complete the workshop will be presented with a certificate from Brookhaven National Laboratory attesting to their skills in **Applied Quantum Computing**. The workshop will run each day, Monday – Friday, for three weeks from June 10 – 28, 2024 from 10:00 AM – 6:00 PM ET (two 1-hour breaks) and be conducted entirely via Zoom web conferencing.

**STIPEND:** \$500 per week

**ELIGIBILITY:** Minimum 18 years of age. Must be a U.S. citizen or Legal Permanent Resident. Must successfully complete the Brookhaven National Laboratory Guest Registration process.

**PREREQUISITES:** Students must have completed all (6) courses listed below prior to program commencement on Jun 10, 2024 with a grade B (3.0 GPA) or better.

- **Computer Programming:** A course covering an “Introduction to Programming” and a course covering “Data Structure & Algorithms”.
- **Math:** A course covering “Linear Algebra with Vectors & Matrices” and a course covering “Differential Equations”.
- **Physics:** A course covering “Physics Using Calculus including Classical Mechanics & Electromagnetism” and a course covering either “Thermodynamics” or “Mathematical Methods in Physics”.

In addition to the above, only applicants who are rising college juniors or seniors (or recent college graduates) and who will have completed the spring 2024 semester by June 10, 2024 will be considered.

## QIS 100: Applied Quantum Computing Virtual Program, June 2025

Application Period Opens February 2025

## Virginia Tech & C2QA QIS & Engineering High School Level Virtual Program, August 2025

Application Period Opens March 2025





# Google Summer of Code 2023

## Introduction

In 2023 ML4SCI is participating in the program as a GSoC umbrella organization. The ML4SCI organization has partnered with the **Google Summer of Code** in 2023 to broaden student participation in machine learning projects over a wide variety of scientific fields. ML4SCI participants will be mentored by scientists at top research universities and laboratories on research projects at the cutting edge of science. Projects span a wide range of scientific domains, including physics, astronomy, planetary science, quantum information science and others.

## For Students

In 2023 GSoC students work with their mentors for 175 hrs to produce open-source codes that apply machine learning solutions to solve science problems. Projects span three evaluation periods that allow for students and mentors to collaborate on their project and evaluate student progress. Detailed rules for the GSOC program can be found **here**. Interested students should look at the ideas page and contact the mentors. Candidates will be asked to complete an evaluation test for each project they apply to demonstrate the skills needed for the respective projects. In the next step, students will produce a





# Google Summer of Code 2023

## Introduction

In 2023 ML4SCI is participating in the program as a GSoC umbrella organization. The ML4SCI organization has partnered with the **Google Summer of Code** in 2023 to broaden student participation in machine learning projects over a wide variety of scientific fields. ML4SCI participants will be mentored by scientists at top research universities and laboratories on research projects at the cutting edge of science. Projects span a wide range of scientific domains, including physics, astronomy, planetary science, quantum information science and others.

## For Students

In 2023 GSoC students work with their mentors for 175 hrs to produce open-source codes that apply machine learning solutions to solve science problems. Projects span three evaluation periods that allow for students and mentors to collaborate on their project and evaluate student progress. Detailed rules for the GSOC program can be found **here**. Interested students should look at the ideas page and contact the mentors. Candidates will be asked to complete an evaluation test for each project they apply to demonstrate the skills needed for the respective projects. In the next step, students will produce a



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# The Adjoint Is All You Need: Characterizing Barren Plateaus in Quantum Ansätze

Enrico Fontana,<sup>1,2</sup> Dylan Herman,<sup>1,\*</sup> Shouvanik Chakrabarti,<sup>1</sup> Niraj Kumar,<sup>1</sup>  
Romina Yalovetzky,<sup>1</sup> Jamie Heredge,<sup>1,3</sup> Shree Hari Sureshababu,<sup>1</sup> and Marco Pistoia<sup>1</sup>

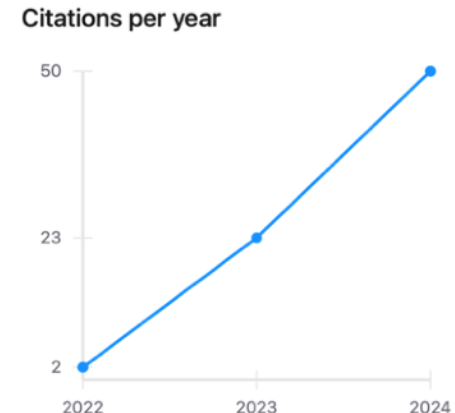
<sup>1</sup>*Global Technology Applied Research, JPMorgan Chase*

<sup>2</sup>*Computer and Information Sciences, University of Strathclyde*

<sup>3</sup>*School of Physics, The University of Melbourne*

Using tools from the representation theory of compact Lie groups, we formulate a theory of Barren Plateaus (BPs) for parameterized quantum circuits whose observables lie in their dynamical Lie algebra (DLA), a setting that we term Lie algebra Supported Ansatz (LASA). A large variety of commonly used ansätze such as the Hamiltonian Variational Ansatz, Quantum Alternating Operator Ansatz, and many equivariant quantum neural networks are LASAs. In particular, our theory provides, for the first time, the ability to compute the variance of the gradient of the cost function of the quantum compound ansatz. We rigorously prove that, for LASA, the variance of the gradient of the cost function, for a 2-design of the dynamical Lie group, scales inversely with the dimension of the DLA, which agrees with existing numerical observations. In addition, to motivate the applicability of our results for 2-designs to practical settings, we show that rapid mixing occurs for LASAs with polynomial DLA. Lastly, we include potential extensions for handling cases when the observable lies outside of the DLA and the implications of our results.

*Nature Commun.* 15 (2024) 1, 7171  
2309.07902



# INTERNSHIP

## Research Technologies Summer Associate Program

(Applications currently closed)

### Program information

Learn more about our Research Technologies internship program

What You'll Do

**Who We're Looking For**

What We Offer

#### Valued qualities

We are seeking colleagues with excellent analytical, quantitative and problem solving skills and demonstrated research ability. We value strong communication skills and the ability to present findings to a non-technical audience.

#### Key skills

- Enrolled in a master's or Ph.D. degree program in computer science, math, engineering, sciences or other quantitative fields
- Experience with quantum computing algorithms and applications
- Excellent knowledge of Python programming
- Working knowledge of common research evaluation frameworks and techniques
- No prior experience with financial markets required



# Engineering Manager, Data Security

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[Apply on company site](#) 



## What we're looking for:

- A strong background in data security. **This could include experience such as:**
  - *Strong understanding of data security principles in modern application contexts*
  - Implementing modern encryptions algorithms
  - *Delivering key management systems, key distribution protocols, or working with hardware security modules*
  - *Identifying and mitigating real-world security vulnerabilities and attack vectors*
- You've managed or technically led a team of developers and owned application development from planning to delivery.
- You bring hands-on engineering experience and have tackled complex, ambiguous problems through code.
- You use your technical background to coach developers and elevate team performance

## Bonus points for:

- Experience with post-quantum cryptography (e.g., lattice-based algorithms) in theory or practice
- Familiarity with evolving cryptographic standards and bodies (e.g., NIST), and how they shape implementation decisions

# Summary

- Quantum computing uses the weirdness of **quantum physics** (like superposition and entanglement) to solve problems in new ways.
- It's **not science fiction** — real quantum computers exist today and are already solving small-scale problems.
- This field combines physics, math, computer science, and engineering — so **whatever you're into, you can be part of it.**
- Quantum computers could revolutionize many areas such as security, medicine, materials, AI, climate modeling, and more.
- It's a **young field** — we need your ideas, your questions, and your creativity.
- **What You Can Do Now:**
  - Get curious: try a quantum simulator (like IBM Quantum Experience).
  - Learn linear algebra and probability — they're the language of quantum.
  - Ask "what if?" — because today's science fiction is tomorrow's technology.



# Very brief history of quantum computing

- 1925 The term “quantum mechanics” used by M. Born (Pauli, Heisenberg from U of Göttingen)
- 1925 Formulation of matrix mechanics by Heisenberg, Born, Jordan
- 1925-1927: Copenhagen interpretation
- 1930 “The principles of quantum mechanics” by Dirac
- 1935 Einstein, Podolsky and Rosen
- 1935 “Quantum entanglement” and Schrödinger’s cat by Schrödinger and Einstein
- 1947 “Spooky action at a distance” in a letter to M. Born by A. Einstein
- 1976 Attempt to create quantum information theory
- 1980 Quantum mechanical model of Turing machine by Benioff (ANL)
- 1981 “Simulating Physics with Computers” by Feynman
- 1985 Quantum Turing machine by Deutsch
- 1992 Deutsch-Jozsa algorithm
- 1993 First paper on quantum teleportation
- 1994 Shor’s factoring algorithm (cf RSA encryption)
- 1996 Grover search algorithm (Bell)
- 2004 First five photon entanglement by China
- 2011 First commercially available quantum computer (D-Wave)
- 2017 First quantum teleportation of independent single-photon qubit (14km) by China
- 2018 US National Quantum Initiative Act.
- 2019 Google quantum supremacy
- 2022 Nobel prize (Aspect, Clauser, Zeilinger) for violation of Bell’s inequality
- 2022 433 qubits by IBM
- 2023 Breakthrough Prize (Bennet, Brassard, Shor, Deutsch)

“Zur Quantenmechanik”  
by Born and Jordan 1925





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THE FEDERAL SOURCE AND GATEWAY TO QUANTUM R&D ACROSS THE U.S. GOVERNMENT

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- [Annual Report on the NQI Program Budget](#), January 6, 2023
- [National Security Memorandum 10 on Quantum Computing](#), May 4, 2022
- [Bringing Quantum Sensors to Fruition](#), March 24, 2022
- [QIST Workforce Development National Strategic Plan](#), February 1, 2022
- [The Role of International Talent in Quantum Information Science](#), October 5, 2021
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# The Nobel Prize in Physics 2022

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© Nobel Prize Outreach. Photo:  
Stefan Bladh

**Alain Aspect**

Prize share: 1/3



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**John F. Clauser**

Prize share: 1/3



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**Anton Zeilinger**

Prize share: 1/3

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The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

Yuri Milner found the Breakthrough prize in 2012.

# FUNDAMENTAL PHYSICS BREAKTHROUGH PRIZE

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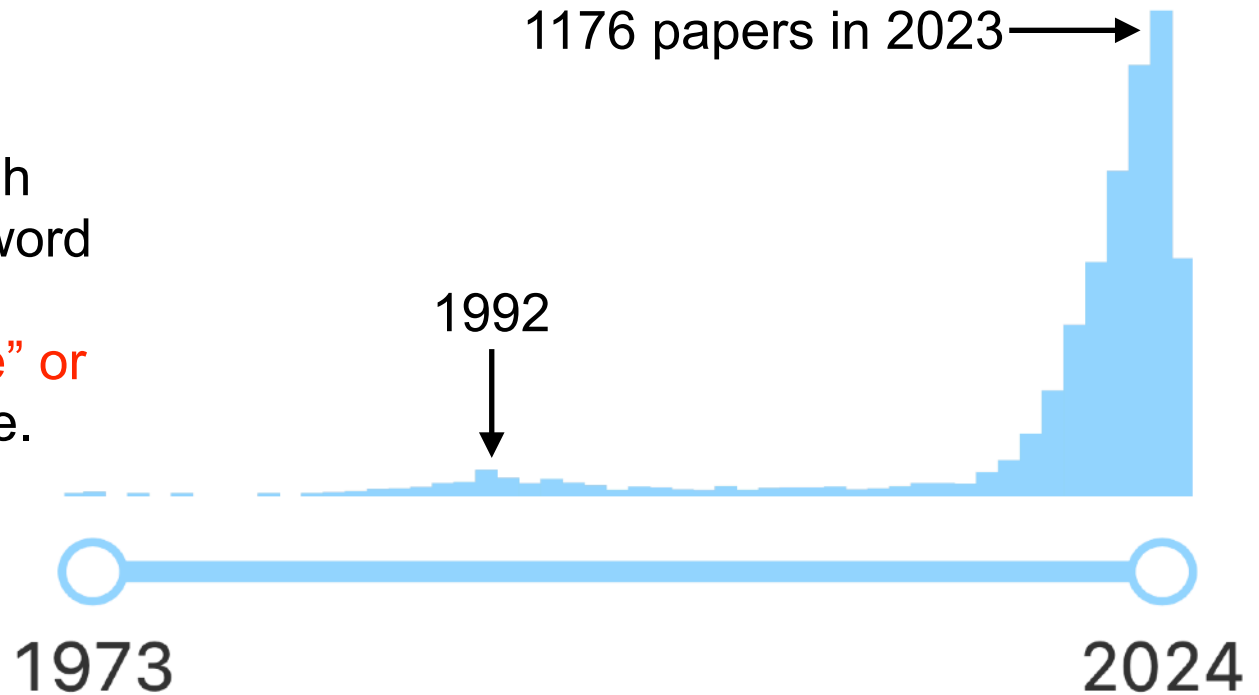
Oxford  
[David Deutsch](#)

BB84, quantum cryptography, factoring algorithms, Deutsch's algorithm



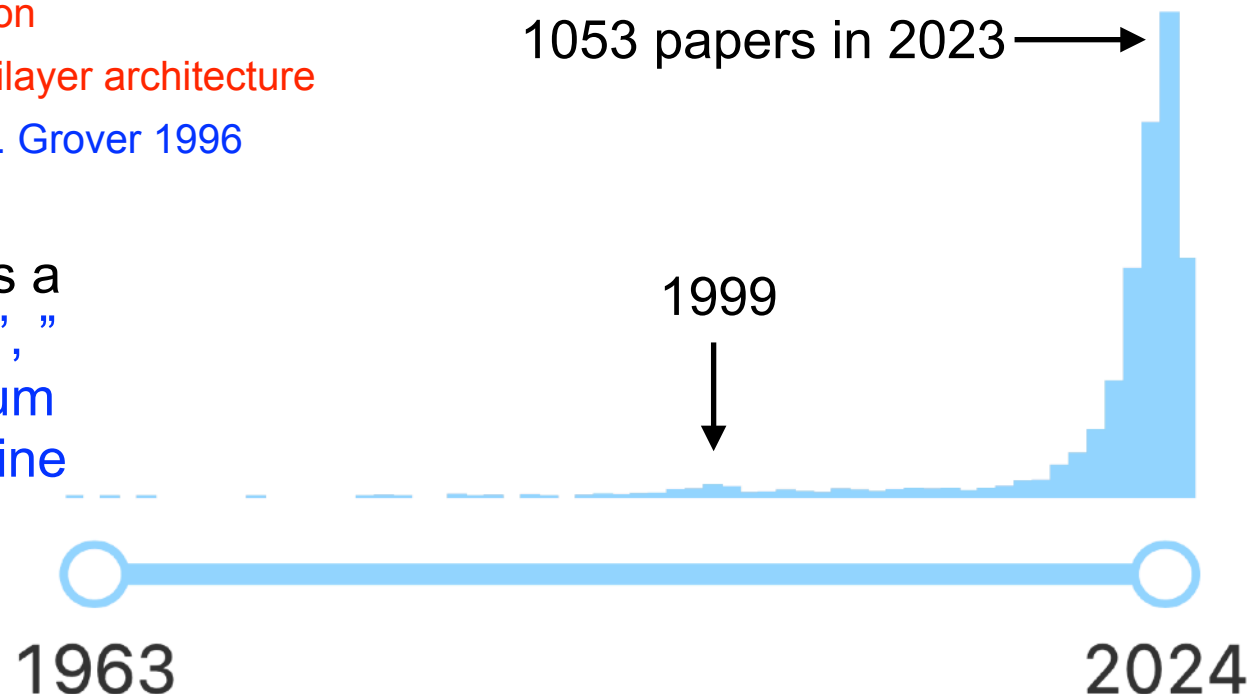
Data is obtained via **InspireHEP**

The number of papers (in high energy physics) that has a keyword “Machine Learning”, “Deep Learning”, “Artificial Intelligence” or “Neural Networks” in their title.



- G. Cybenko, 1989 with sigmoid activation
- K. Hornik, 1991, importance of the multilayer architecture
- D Simon, 1993, P. Shor 1994, 1995, L. Grover 1996

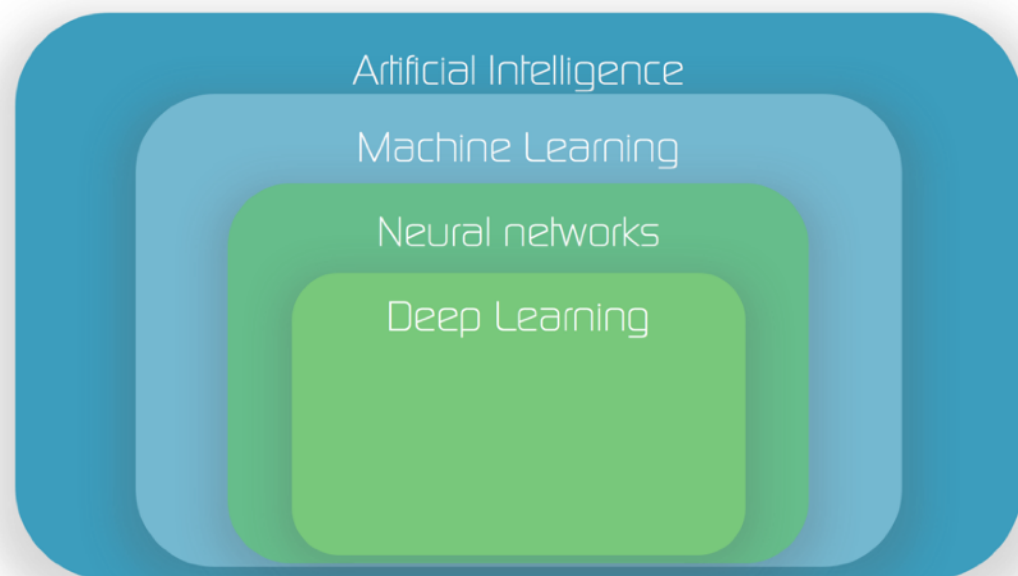
The number of papers that has a keyword “Quantum Computer”, “Quantum Computing”, “Quantum Annealing” or “Quantum Machine Learning” in their title.



Machine Learning?

# What is Machine Learning?

- Typically problems in physics can be formulated in terms of a search for some function  $f : \mathbb{X} \rightarrow \mathbb{Y}$ , from the space of the observed  $\mathbb{X}$  to a low dimensional space of a desired target space/label  $\mathbb{Y}$ , which optimizes some metric (of our choice). The metric is often called a loss function and written as  $L(\vec{y}, f(\vec{x}))$ .
- A learning algorithm would find the function that optimizes  $L$  over all possible values of  $(\vec{x}, \vec{y})$ .
- But this is intractable owing to the curse of dimensionality and an infinite number of functions to choose from. Instead one has labeled training data  $\{\vec{x}_i, \vec{y}_i\}_{i=1}^N$  sampled from  $p(\vec{x}, \vec{y})$ . Furthermore the function space is restricted to a model - a highly flexible family of functions  $f_\phi(\vec{x})$  parameterized by  $\phi$ .
- Sounds familiar?



# Universal Approximation Theorem

- A feed-forward network with a single hidden layer containing a finite number of neurons can approximate continuous functions on compact subsets of  $\mathbb{R}^n$  under mild assumptions on the activation function.

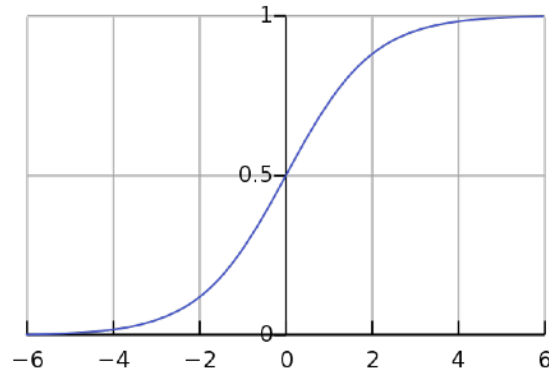
Let  $\varphi : \mathbb{R} \rightarrow \mathbb{R}$  be a nonconstant, bounded, and continuous function (called the *activation function*). Let  $I_m$  denote the  $m$ -dimensional unit hypercube  $[0, 1]^m$ . The space of real-valued continuous functions on  $I_m$  is denoted by  $C(I_m)$ . Then, given any  $\varepsilon > 0$  and any function  $f \in C(I_m)$ , there exist an integer  $N$ , real constants  $v_i, b_i \in \mathbb{R}$  and real vectors  $w_i \in \mathbb{R}^m$  for  $i = 1, \dots, N$ , such that we may define:

$$F(x) = \sum_{i=1}^N v_i \varphi(w_i^T x + b_i) \quad \text{as an approximate realization of the function } f; \text{ that is,}$$

$|F(x) - f(x)| < \varepsilon$  for all  $x \in I_m$ . In other words, functions of the form  $F(x)$  are dense in  $C(I_m)$ .

- A. N. Kolmogorov, 1957
- G. Cybenko, 1989 with sigmoid activation
- K. Hornik, 1991, importance of the multilayer architecture
- Z. Lu et al, 2017, with deep neural network and ReLu activation

$$S(x) = \frac{1}{1 + e^{-x}} = \frac{e^x}{e^x + 1}$$



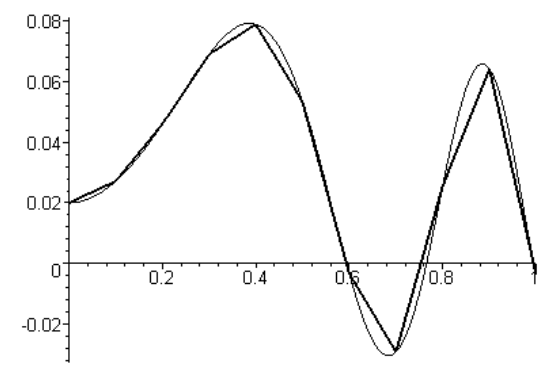
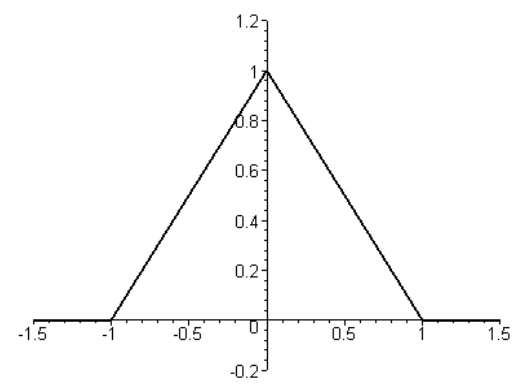
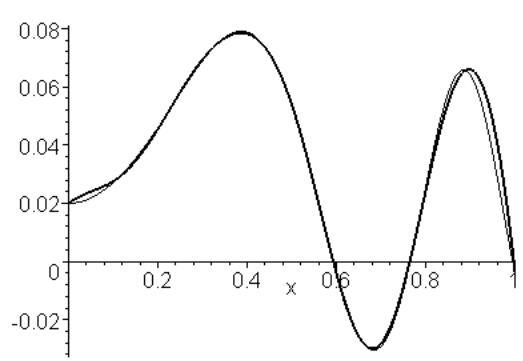
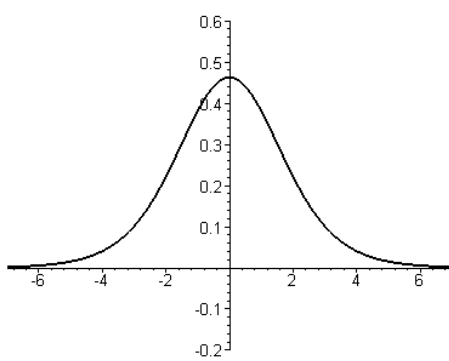
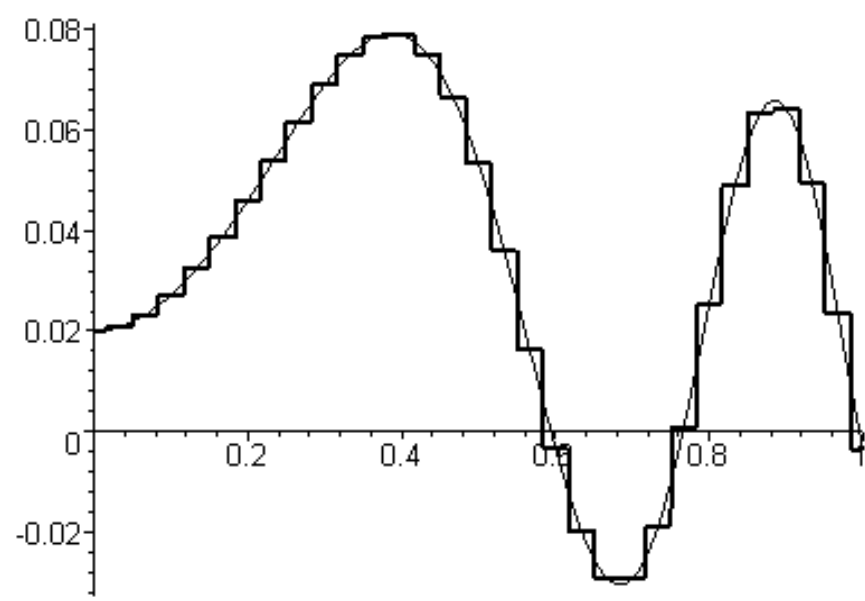
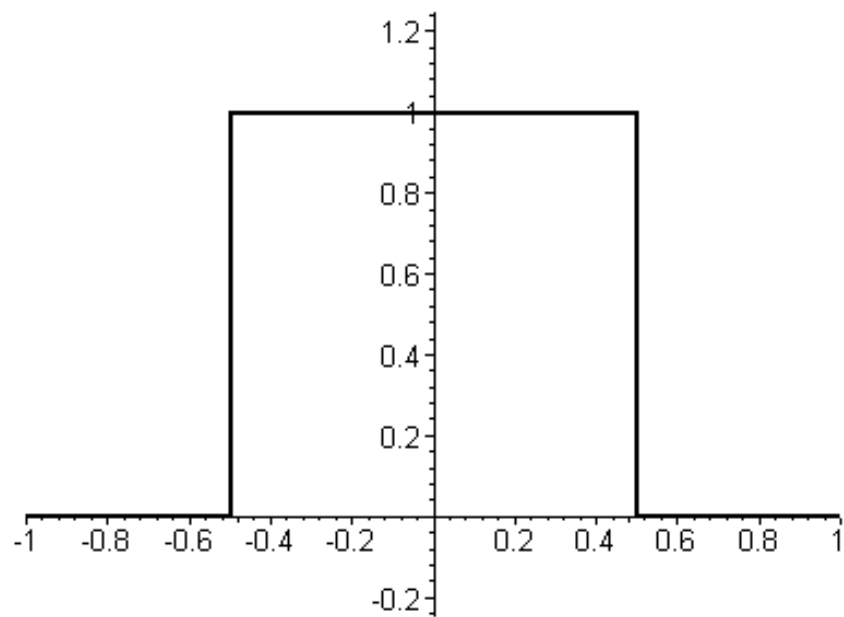


Let  $p > 0$  be a fixed number and  $f(x)$  be a periodic function with period  $2p$ , defined on  $(-p, p)$ . The Fourier series of  $f(x)$  is a way of expanding the function  $f(x)$  into an infinite series involving sines and cosines:

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(\frac{n\pi x}{p}\right) + \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi x}{p}\right) \quad (2.1)$$

where  $a_0$ ,  $a_n$ , and  $b_n$  are called the Fourier coefficients of  $f(x)$ , and are given by the formulas

$$\begin{aligned} a_0 &= \frac{1}{p} \int_{-p}^p f(x) \, dx, & a_n &= \frac{1}{p} \int_{-p}^p f(x) \cos\left(\frac{n\pi x}{p}\right) \, dx, \\ b_n &= \frac{1}{p} \int_{-p}^p f(x) \sin\left(\frac{n\pi x}{p}\right) \, dx, \end{aligned} \quad (2.2)$$

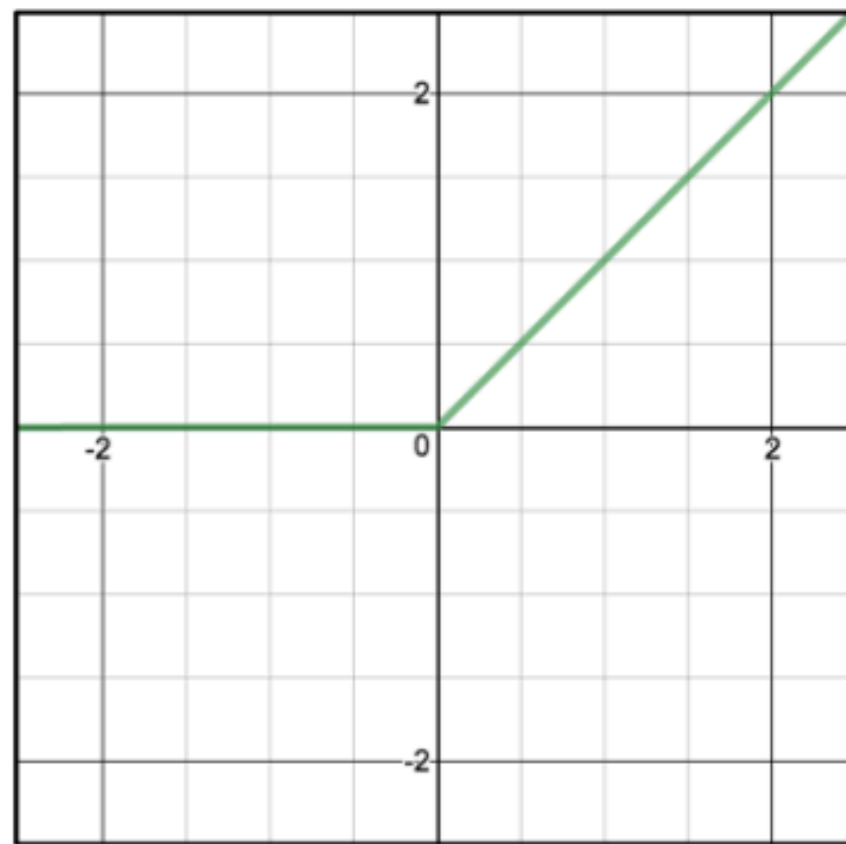
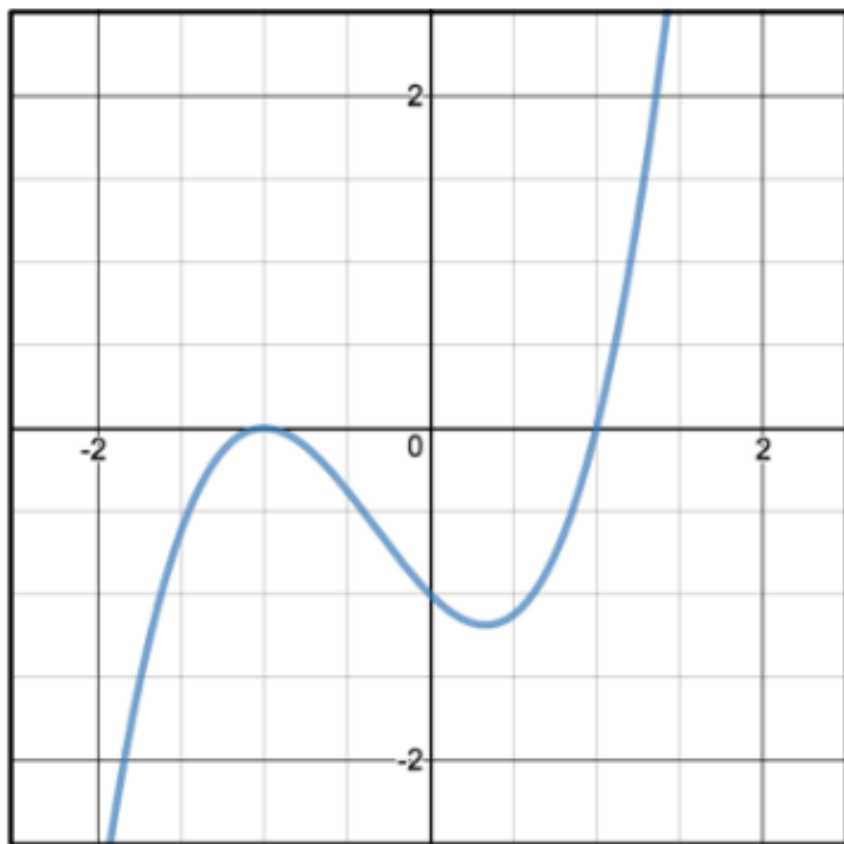


Neural network is a function-approximator.

Rectified Linear Unit

$$f(x) = x^3 + x^2 - x - 1$$

ReLU



$$\text{ReLU} = \max(0, x)$$

$$f(x) = x^3 + x^2 - x - 1$$



$$n_1(x) = \text{Relu}(-5x - 7.7)$$

$$n_2(x) = \text{Relu}(-1.2x - 1.3)$$

$$n_3(x) = \text{Relu}(1.2x + 1)$$

$$n_4(x) = \text{Relu}(1.2x - .2)$$

$$n_5(x) = \text{Relu}(2x - 1.1)$$

$$n_6(x) = \text{Relu}(5x - 5)$$

$$F(x) = -n_1(x) - n_2(x) - n_3(x) \\ + n_4(x) + n_5(x) + n_6(x)$$



$$n_1(x) = \text{Relu}(-5x - 7.7)$$

$$n_2(x) = \text{Relu}(-1.2x - 1.3)$$

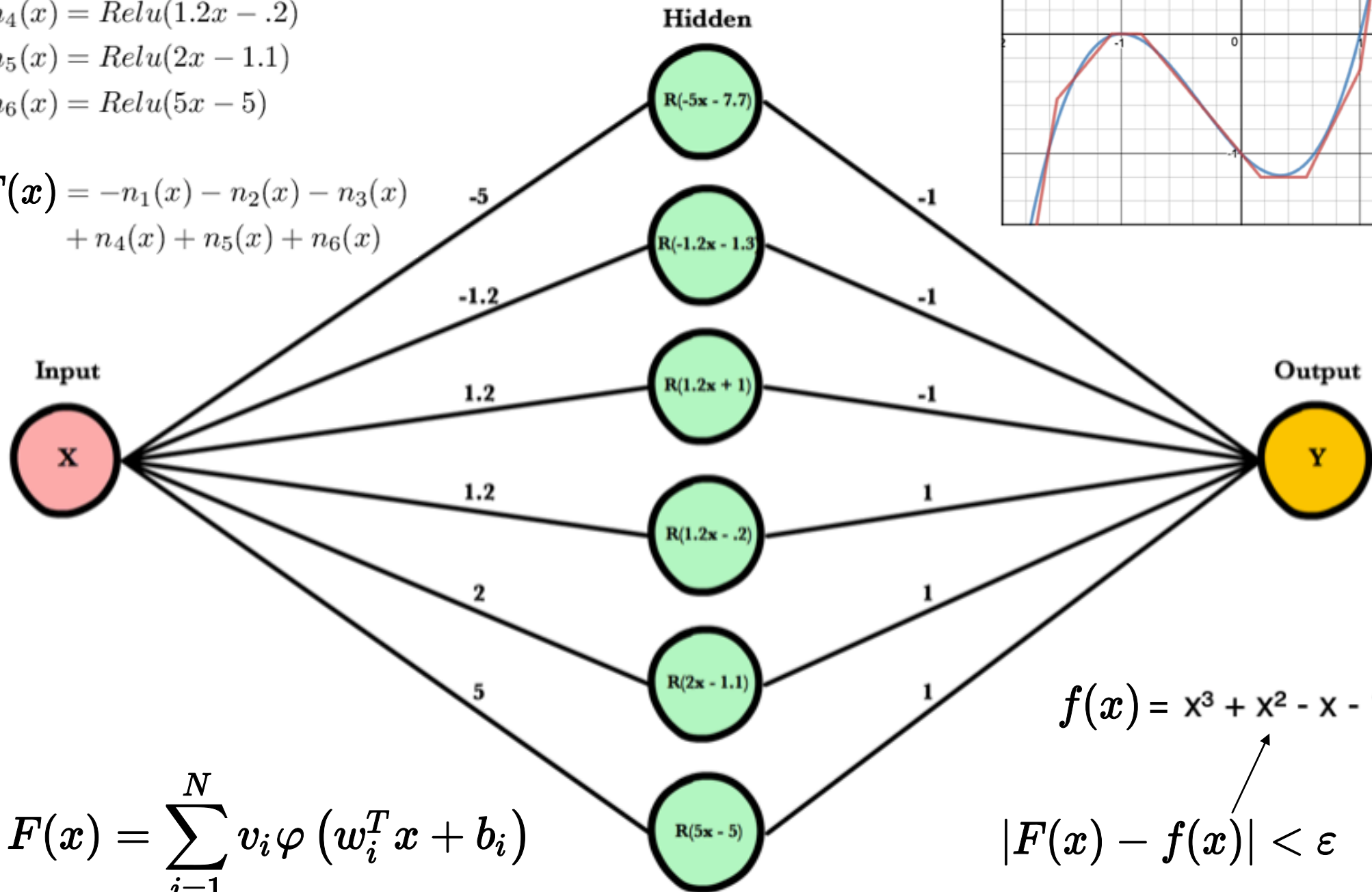
$$n_3(x) = \text{Relu}(1.2x + 1)$$

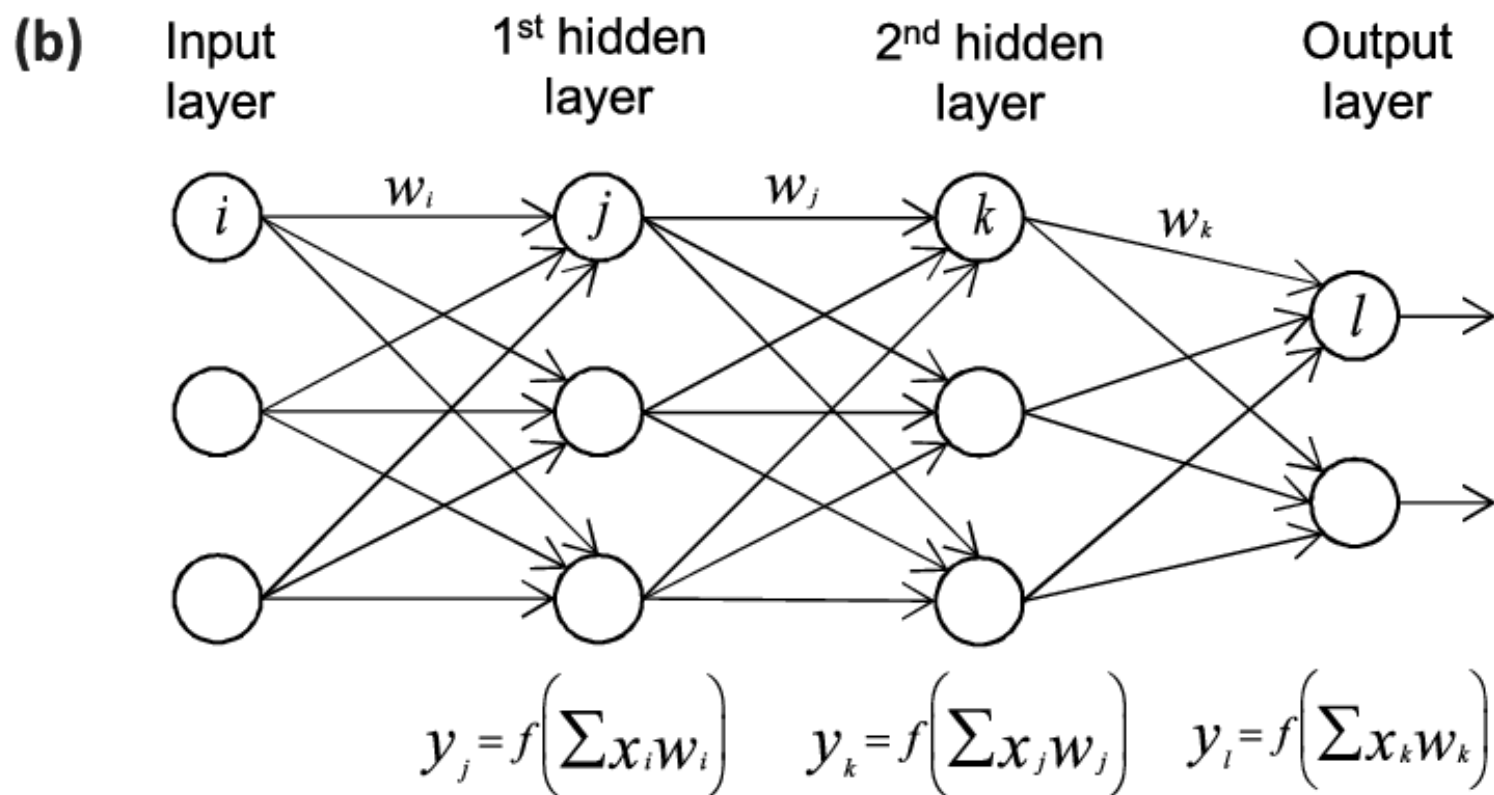
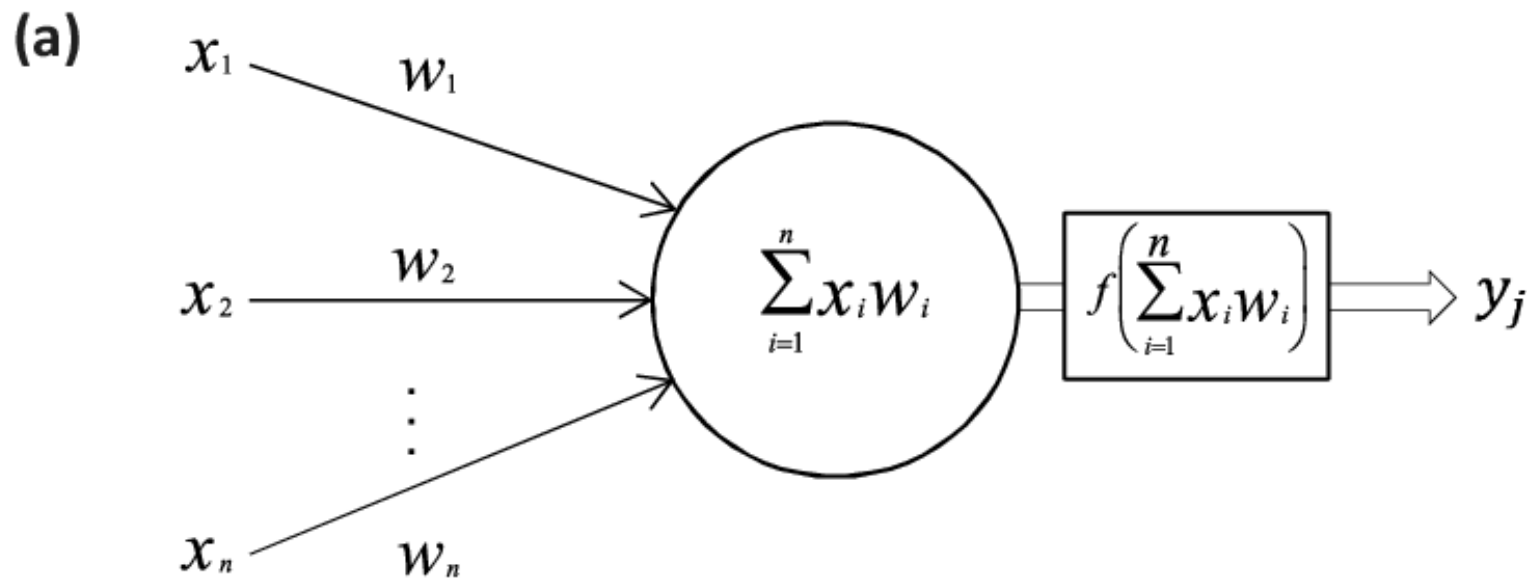
$$n_4(x) = \text{Relu}(1.2x - .2)$$

$$n_5(x) = \text{Relu}(2x - 1.1)$$

$$n_6(x) = \text{Relu}(5x - 5)$$

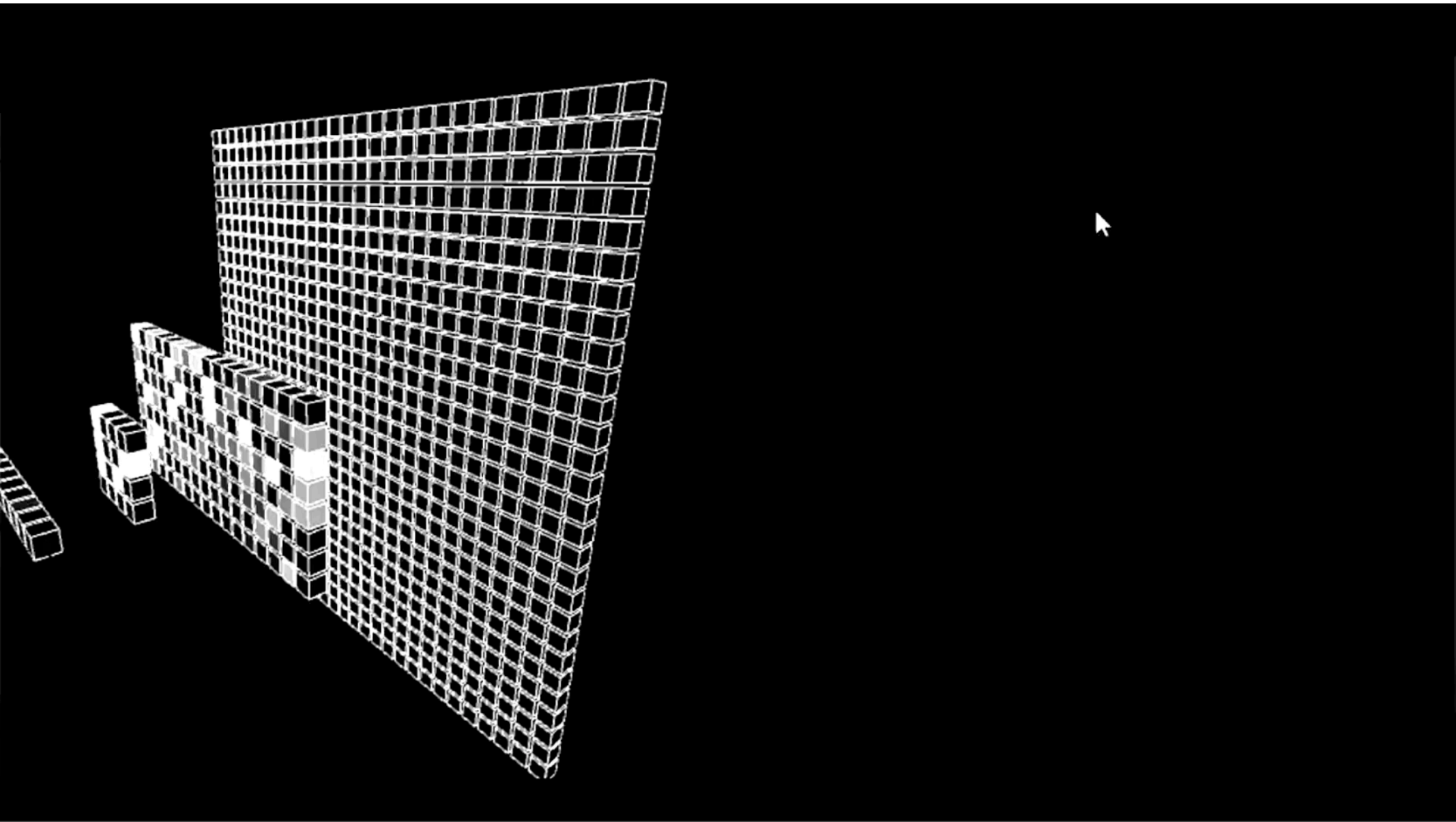
$$F(x) = -n_1(x) - n_2(x) - n_3(x) + n_4(x) + n_5(x) + n_6(x)$$





# Object identification

Taken from Vecanoi (Youtube Educational channel about AI)



# Object identification

Taken from Vecanoi (Youtube Educational channel about AI)

