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

K.C. Kong
University of Kansas

Workshop for AI-Powered Materials Discovery at Great Plains
Jun 22 – 25, 2025

UNIVERSITY OF SOUTH DAKOTA

Plan

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

- Part II
  - $ vs tiger
  - Quantum optimization

About me

- PhD in Theoretical Particle Physics, working on new physics models (extra dimensions, supersymmetry, dark matter etc)
- 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
- No experience with teaching K-12 students

Presentations on quantum computing at this workshop

- From Bits to Qubits: A Beginner’s Journey into Quantum Computing (Tuesday, KC Kong)
- Quantum Computing for Machine Learners: A New Frontier (Tuesday, KC Kong)
- Enhancing quantum utility: Simulating large-scale quantum spin chains on superconducting quantum computers (Tuesday, Talal Chowdhury)
- Quantum Machine Learning Applications in High Energy Physics and Beyond (Wednesday, Konstantin Matchev)
- More talks on quantum physics
- Many talks on AI education and outreach program

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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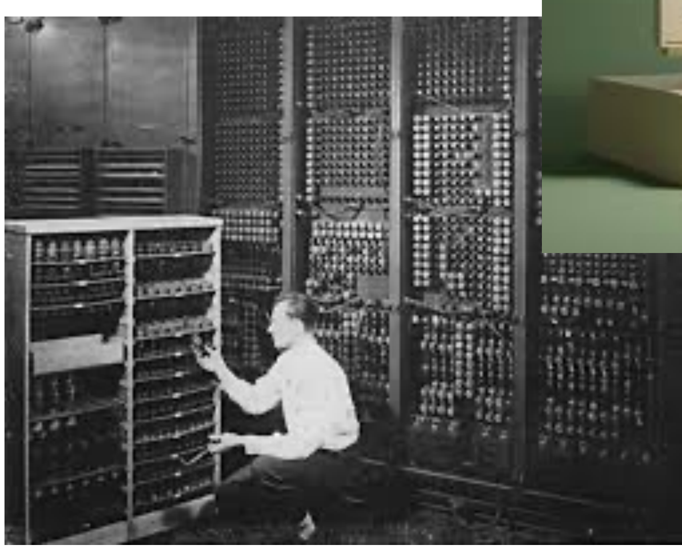
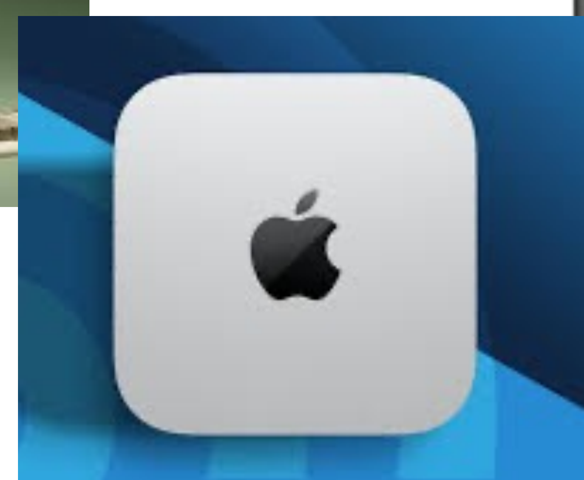
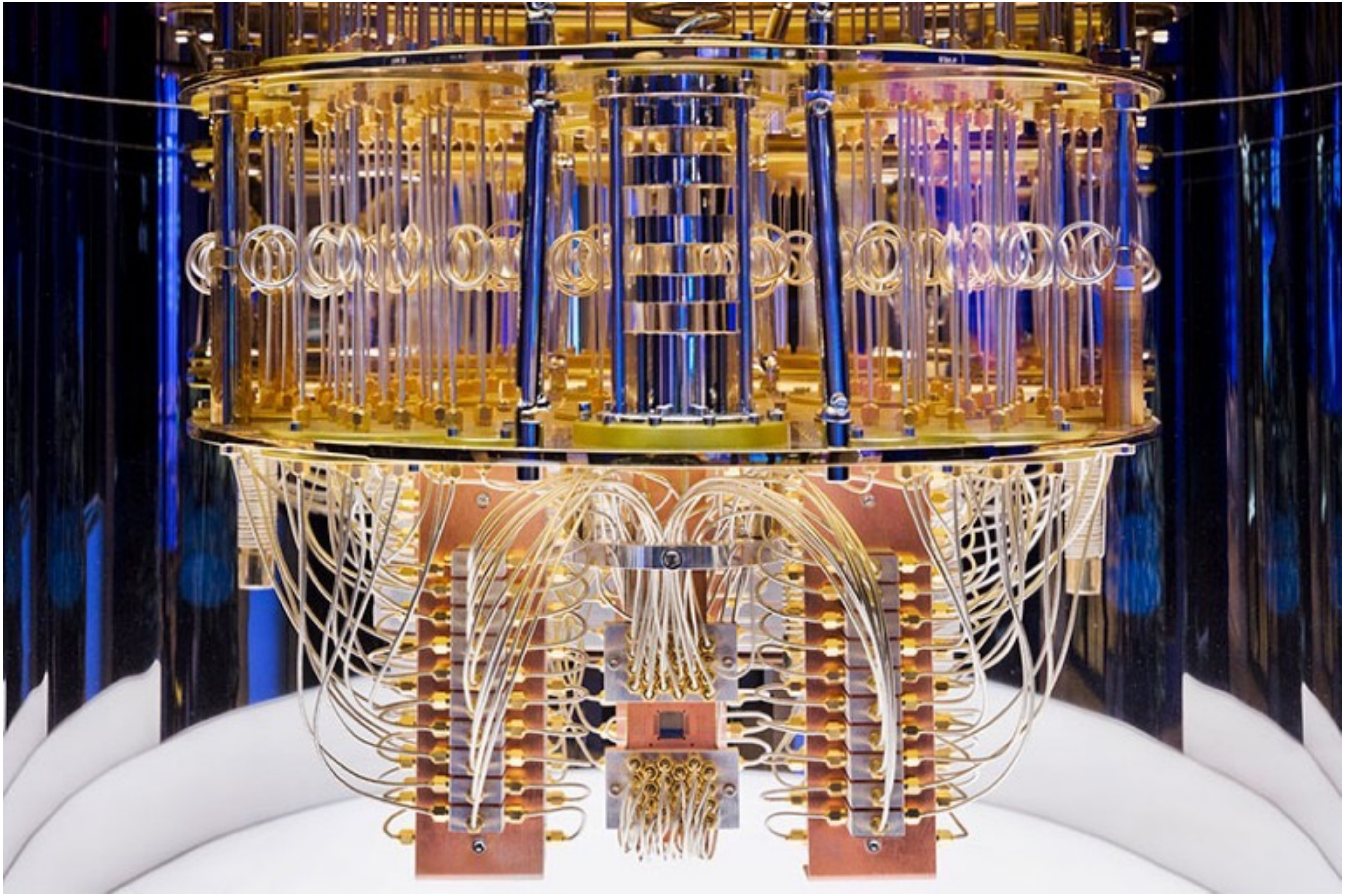






Eagle 127 qubit
IBM Quantum computer
Tens of million dollars
(depending on service contract)

IBM | Quantum | Technology | Qiskit | Research | Pricing | Blog | Community | Resources | Sign in to Platform ↗

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

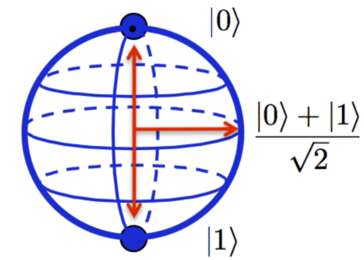
By Thomas Wong

- 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.

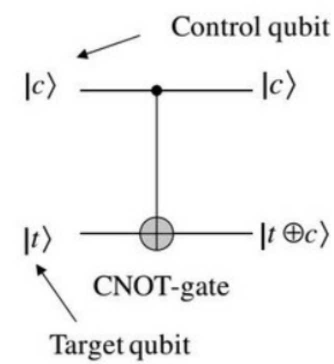
Need transition form classical to quantum:

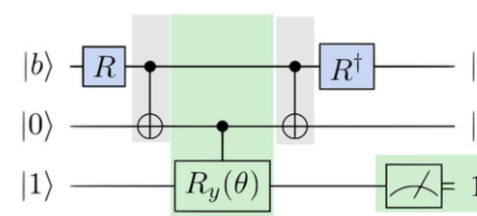
Classical Bit



Qubit

Classical		Quantum
bits	⟷	qubits
gates	⟷	quantum gates
algorithms	⟷	quantum algorithms





classical gates

AND Gate

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Boolean Expression

Y = A . B

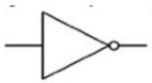
OR Gate

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Boolean Expression

Y = A + B

NOT Gate



A	Y
0	1
1	0

Boolean Expression

Y = A'

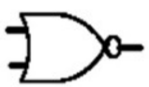
NAND Gate

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

Boolean Expression

Y = (A . B)' = A' + B'

NOR Gate



A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Boolean Expression

Y = (A + B)'

XOR Gate

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Boolean Expression

Y = A ⊕ B

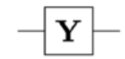
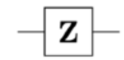
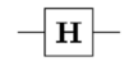
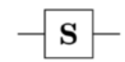
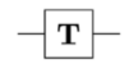
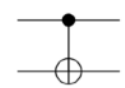
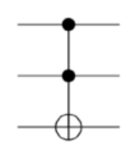
XNOR Gate

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

Boolean Expression

Y = A ⊙ B

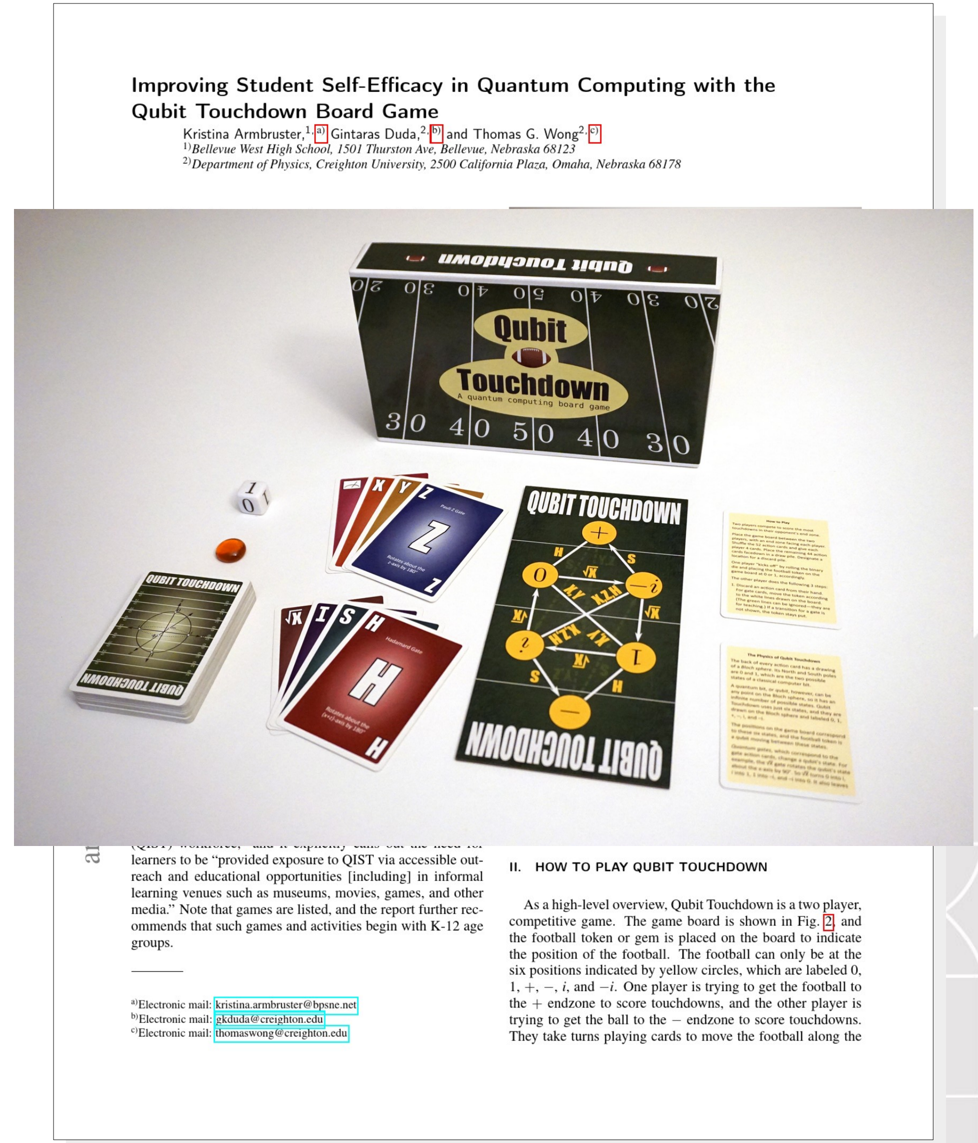
Quantum gates

Operator	Gate(s)	Matrix
Pauli-X (X)		$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)		$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)		$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)		$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP		$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$

Qubit Touchdown

- A quantum computing board game
  - Released Dec. 2019
- Make your own copy – instructions at thomaswong.net
- Buy a professionally produced copy print-on-demand at 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,[1,a] Gintaras Duda,[2,b] and Thomas G. Wong[2,c]
[1]*Bellevue West High School, 1501 Thurston Ave, Bellevue, Nebraska 68123*
[2]*Department of Physics, Creighton University, 2500 California Plaza, Omaha, Nebraska 68178*

learners to be "provided exposure to QIST via accessible outreach and educational opportunities [including] in informal learning venues such as museums, movies, games, and other media." Note that games are listed, and the report further recommends that such games and activities begin with K-12 age groups.

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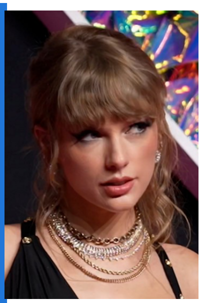
[c]Electronic mail: thomaswong@creighton.edu

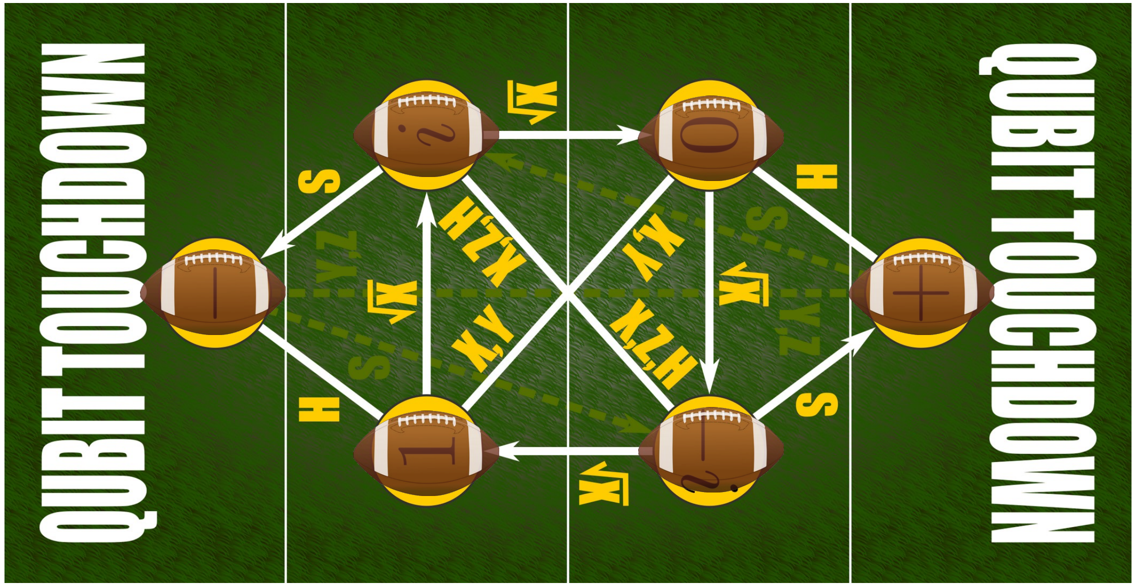
II. HOW TO PLAY QUBIT TOUCHDOWN

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

Touchdown slides are taken from Tom Wong's presentation at QIST workshop 2025

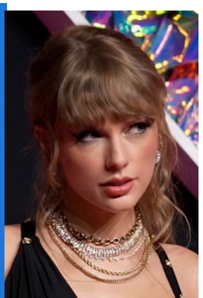


Taylor

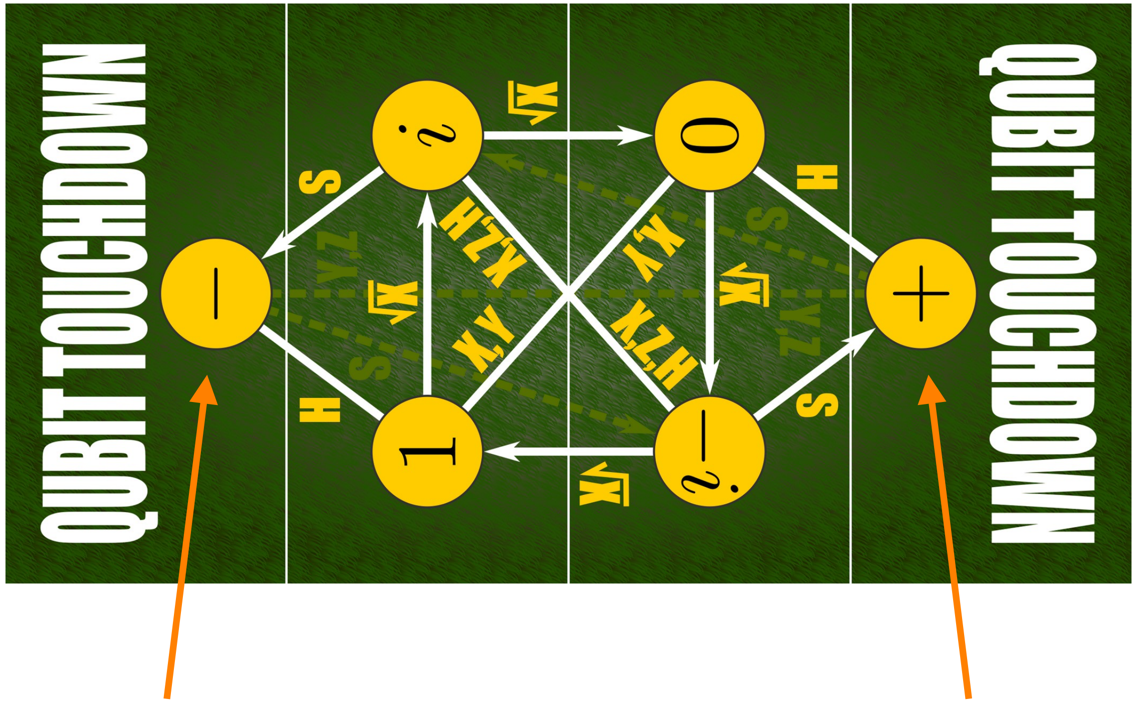


Ryan

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



Taylor

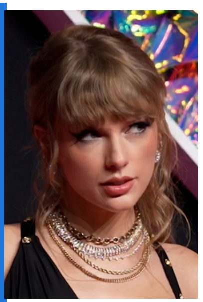


Ryan Scores

Taylor Scores

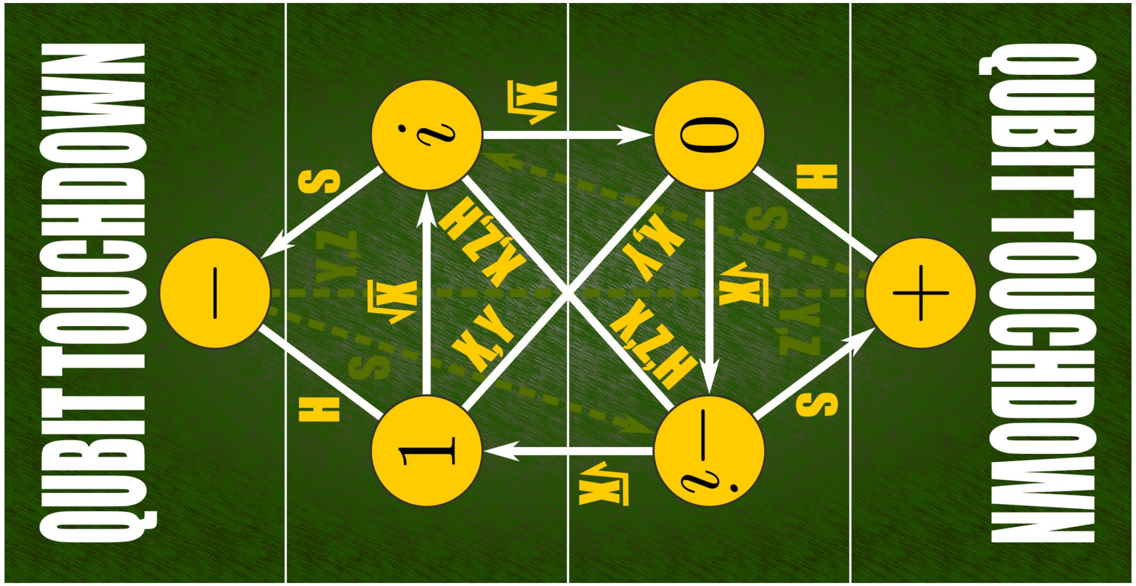
Ryan

- Taylor is trying to get the ball to the "+" endzone, and Ryan is trying to get the ball to the "–" endzone, to score touchdowns.



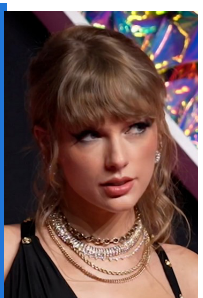
Taylor

Ryan



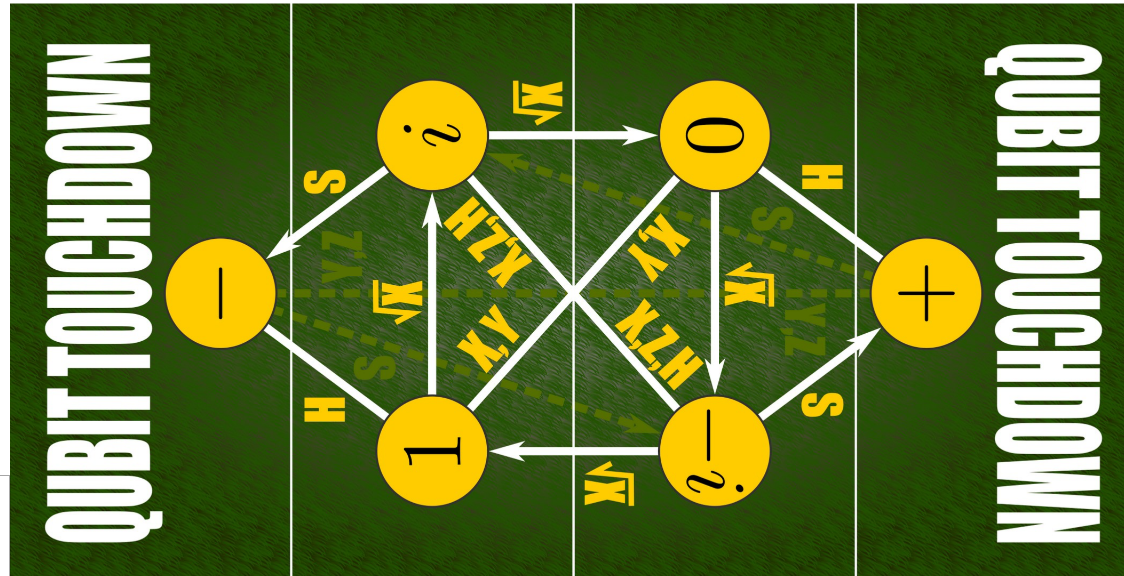
- They take turns playing cards to move the ball along the lines/arrows.
- Whoever scores the most touchdowns by the time all 52 cards are played wins.

Let’s play Qubit touchdown!



Taylor

Touchdowns: 0

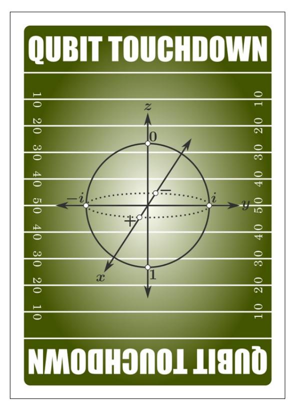


Ryan

Touchdowns: 0

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

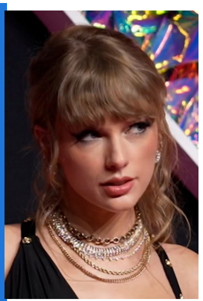
Draw Pile



44 cards

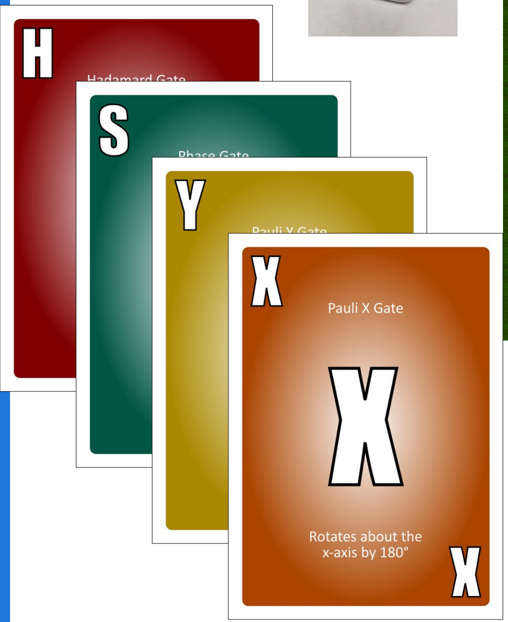
Discard Pile

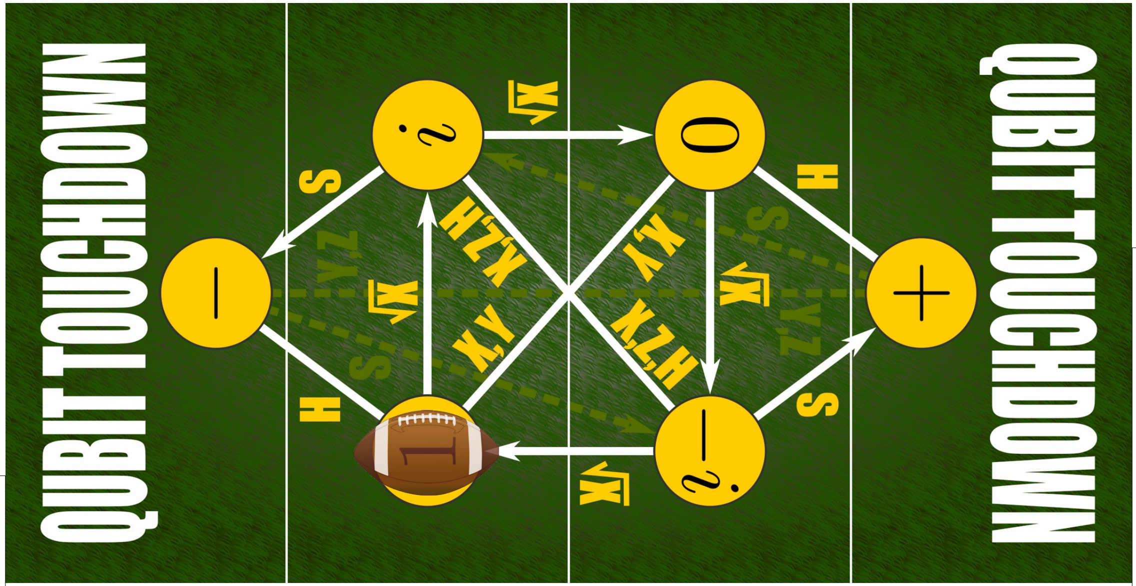
0 cards



Taylor

Touchdowns: 0



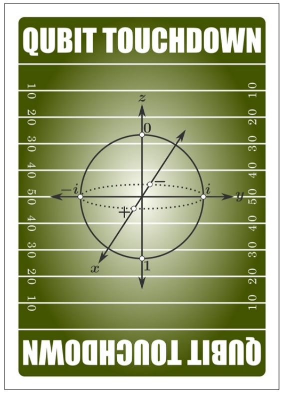


Ryan

Touchdowns: 0

Draw Pile

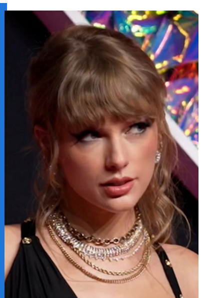
Discard Pile



44 cards

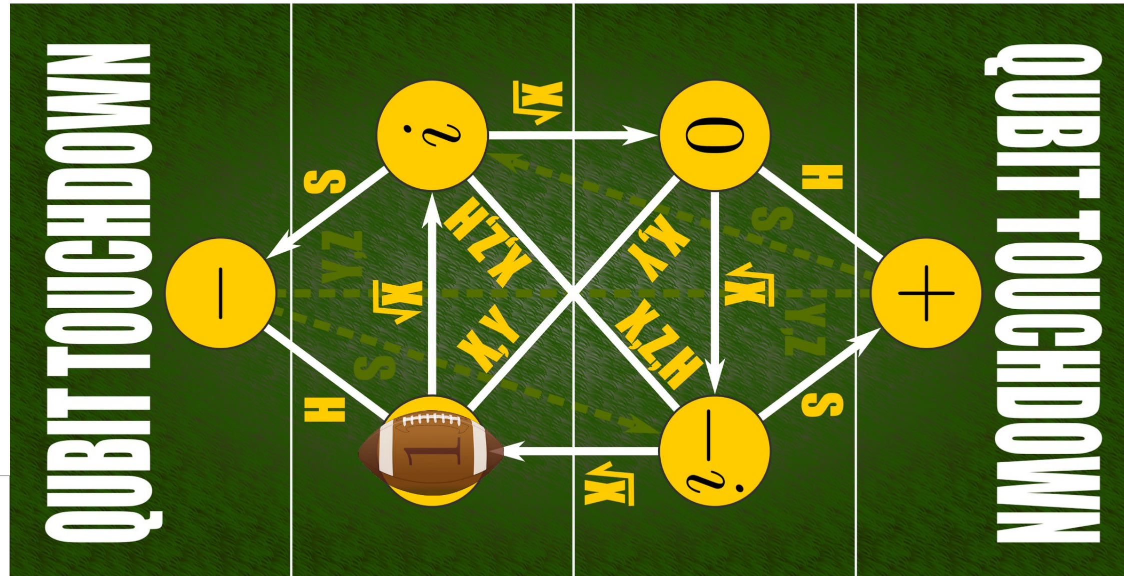
0 cards

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



Taylor

Touchdowns: 0

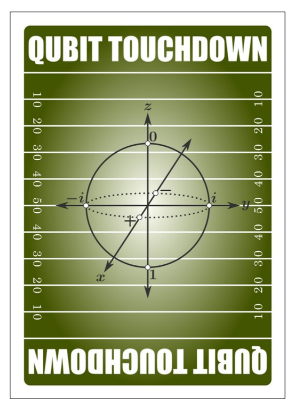


Ryan

Touchdowns: 0

Draw Pile

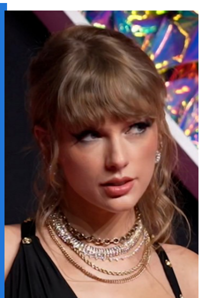
Discard Pile



44 cards

0 cards

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

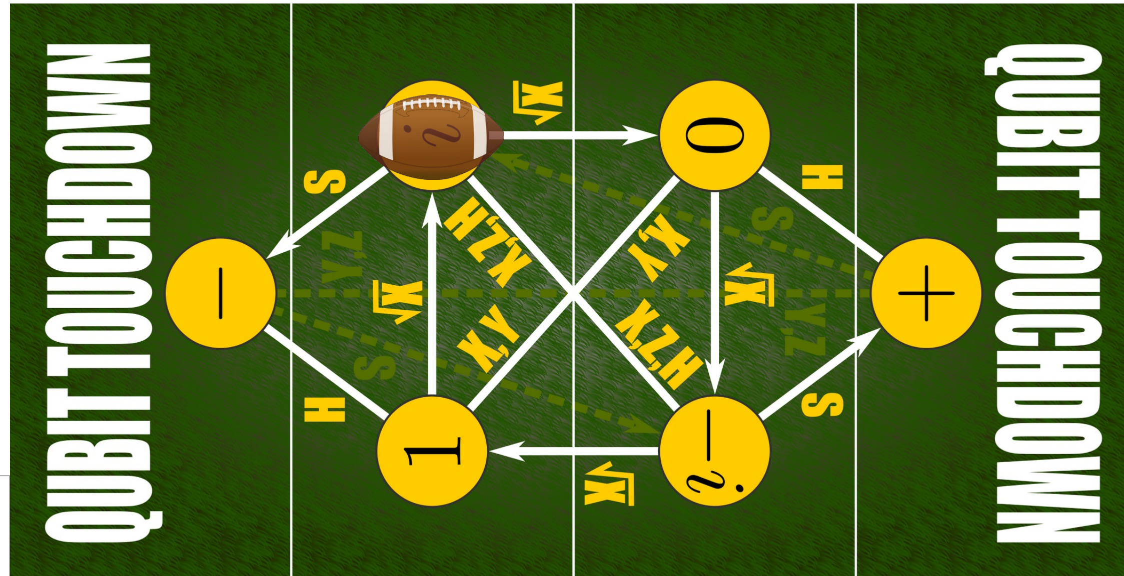


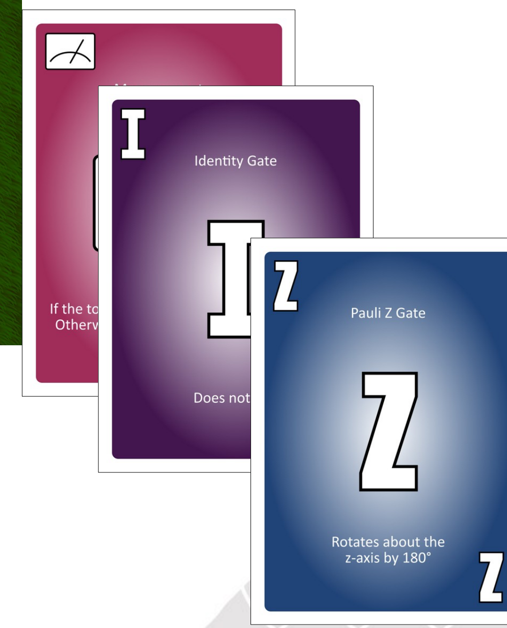
Taylor

Touchdowns: 0

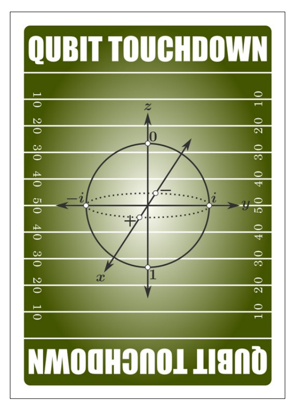
Ryan

Touchdowns: 0



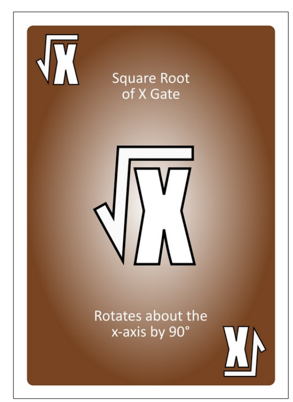


Draw Pile



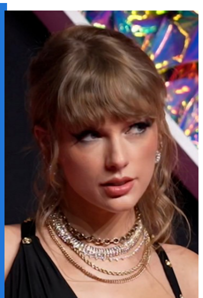
44 cards

Discard Pile



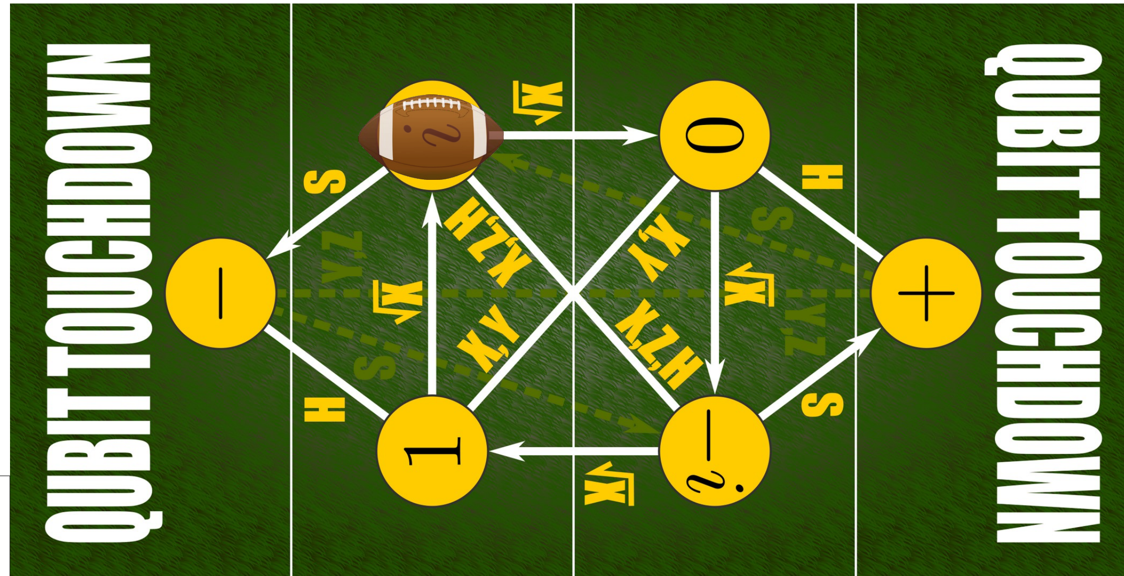
1 card

- He plays "√X" and moves the ball to "i."



Taylor

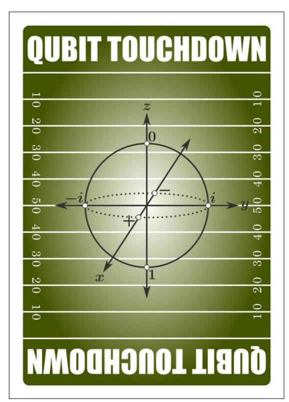
Touchdowns: 0



Ryan

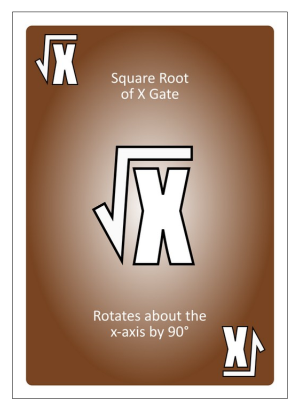
Touchdowns: 0

Draw Pile



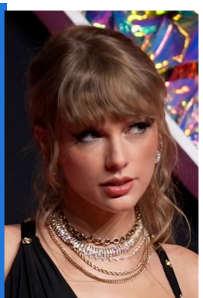
43 cards

Discard Pile



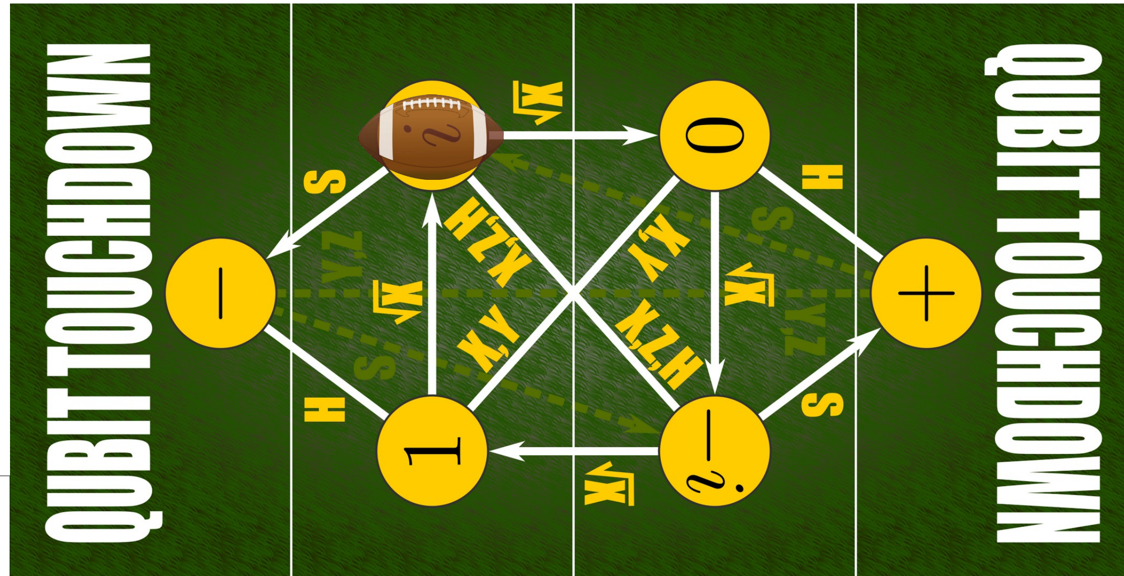
1 card

- He draws a new card.



Taylor

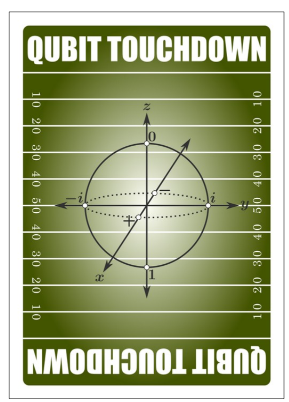
Touchdowns: 0



Ryan

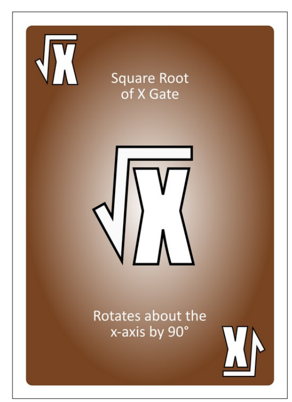
Touchdowns: 0

Draw Pile



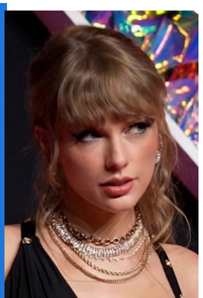
43 cards

Discard Pile



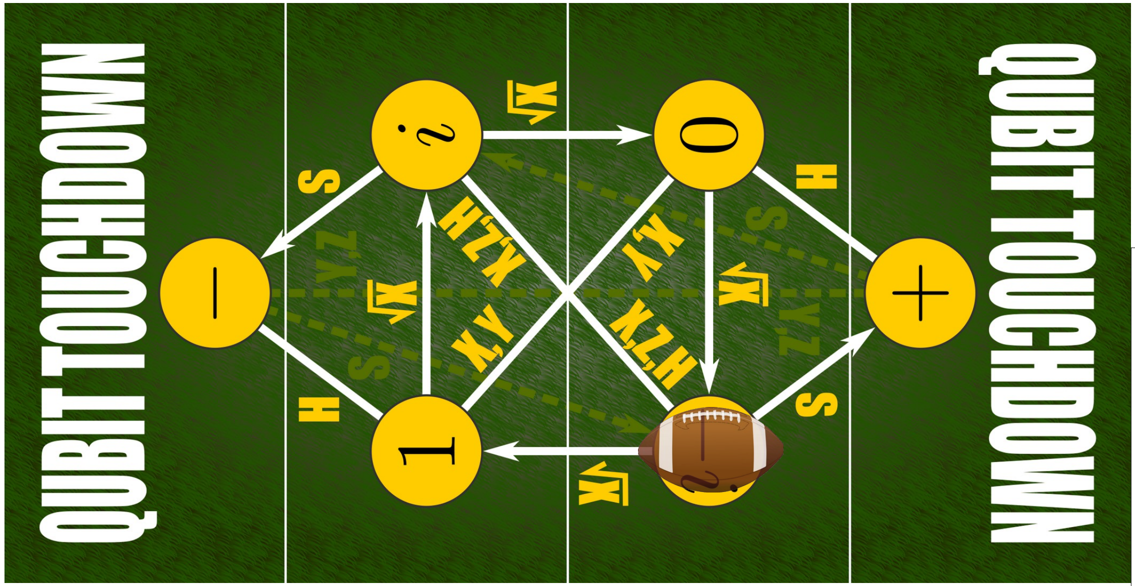
1 card

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



Taylor

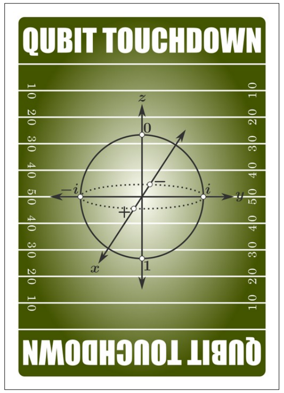
Touchdowns: 0



Ryan

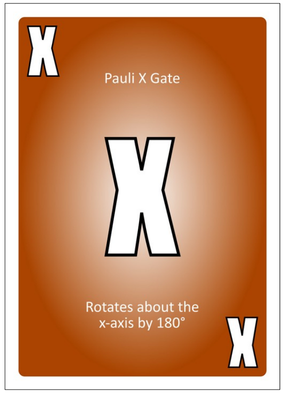
Touchdowns: 0

Draw Pile



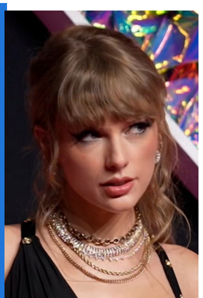
43 cards

Discard Pile



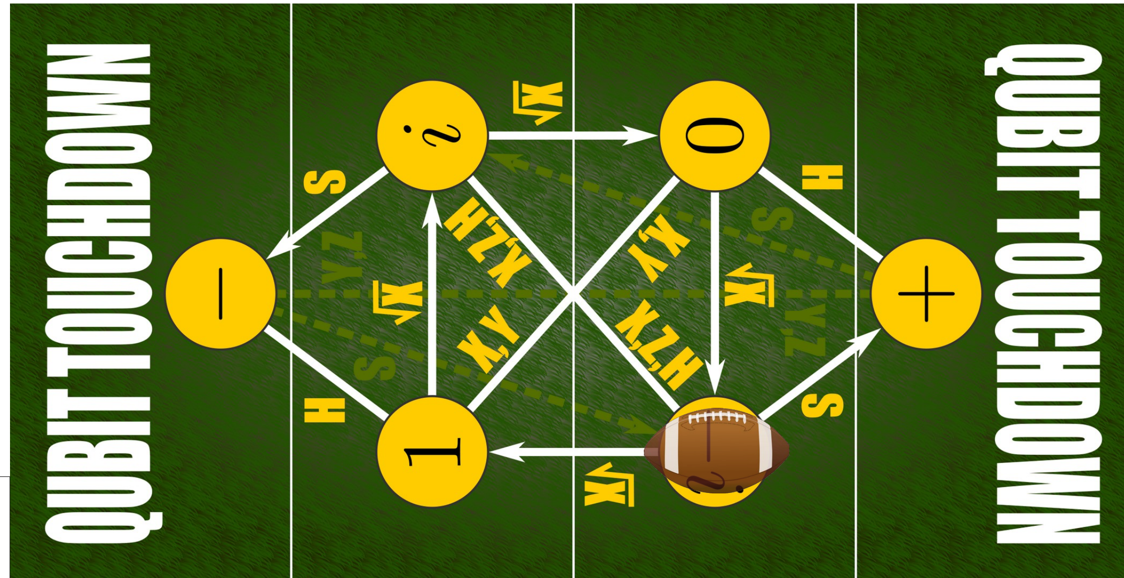
2 cards

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



Taylor

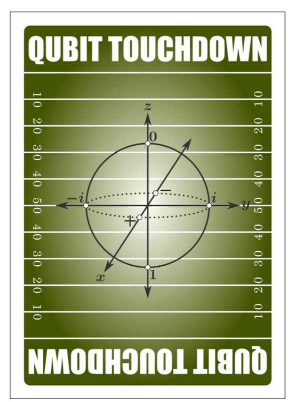
Touchdowns: 0



Ryan

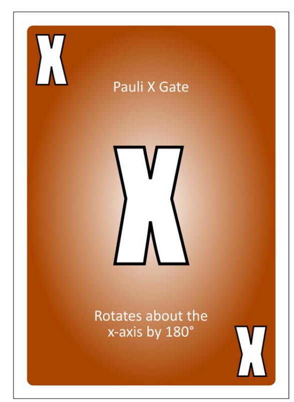
Touchdowns: 0

Draw Pile



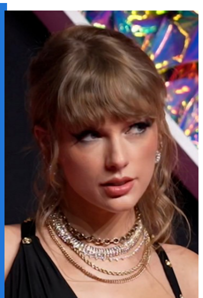
42 cards

Discard Pile



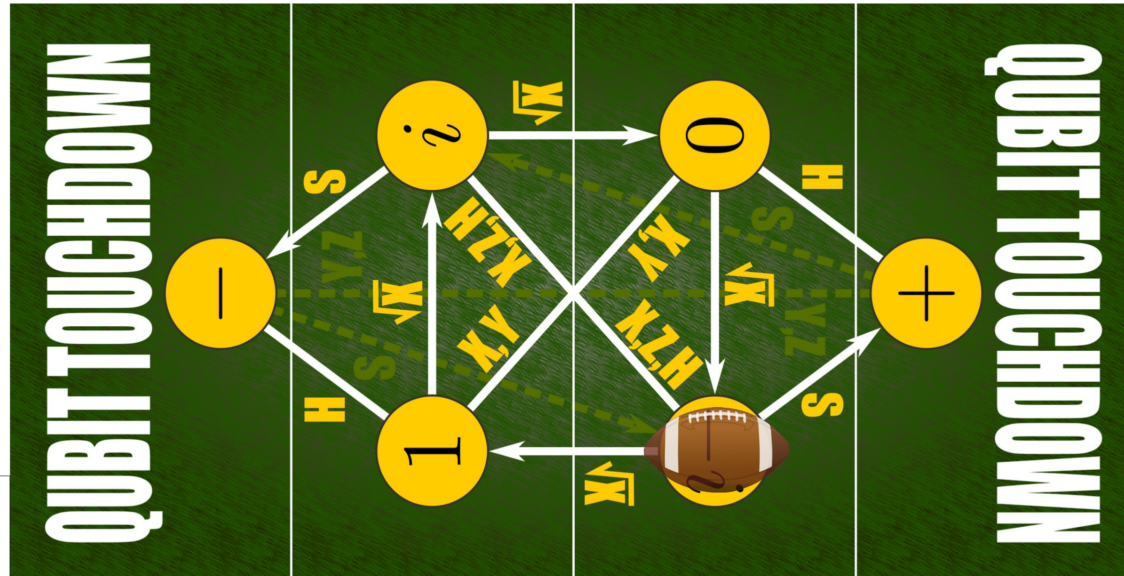
2 cards

- She draws a new card.



Taylor

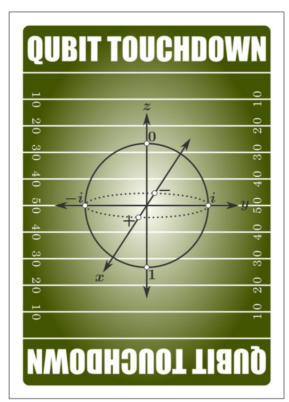
Touchdowns: 0



Ryan

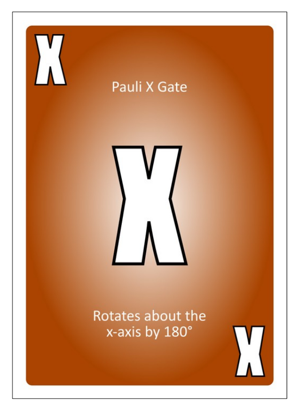
Touchdowns: 0

Draw Pile



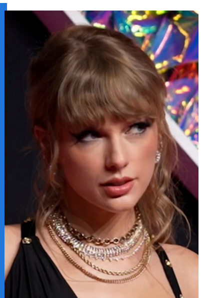
42 cards

Discard Pile



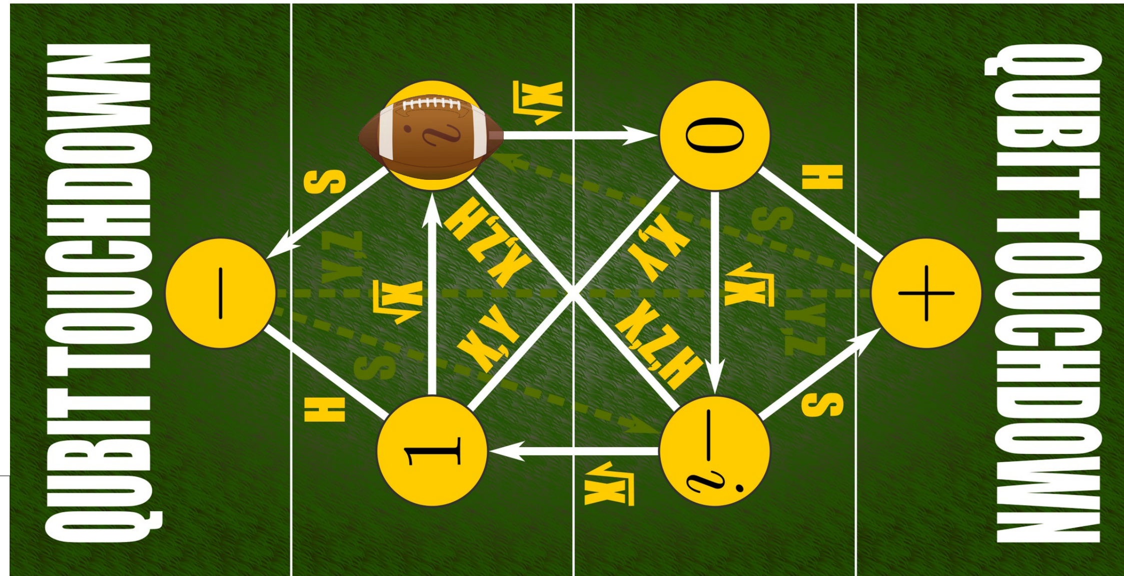
2 cards

- Ryan's turn.



Taylor

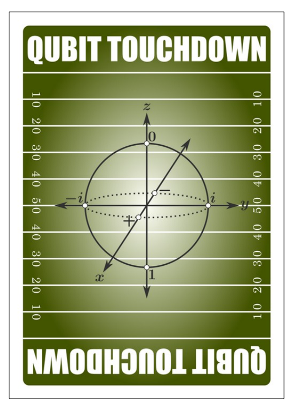
Touchdowns: 0



Ryan

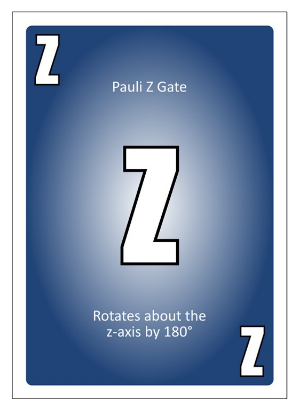
Touchdowns: 0

Draw Pile



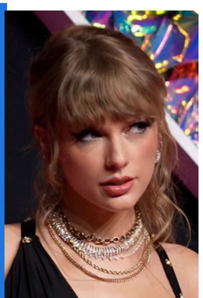
42 cards

Discard Pile



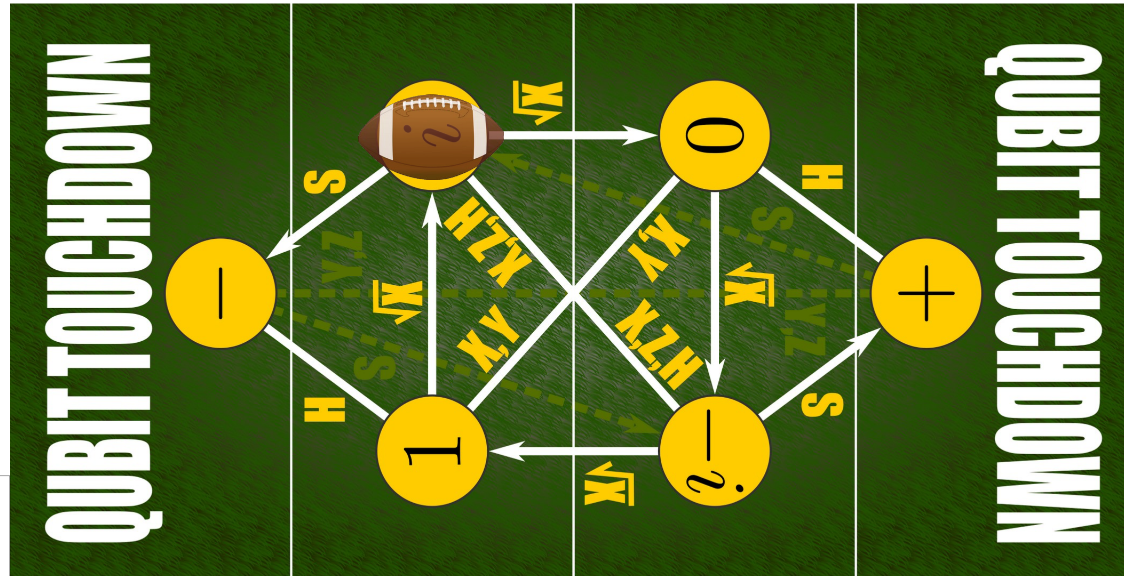
3 cards

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



Taylor

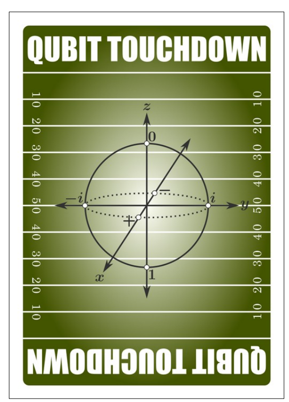
Touchdowns: 0



Ryan

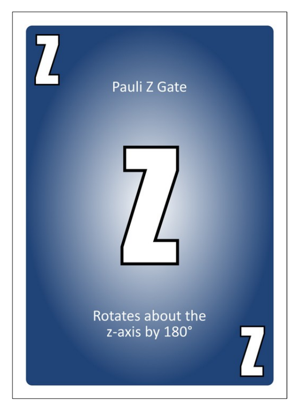
Touchdowns: 0

Draw Pile



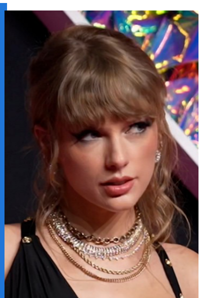
41 cards

Discard Pile



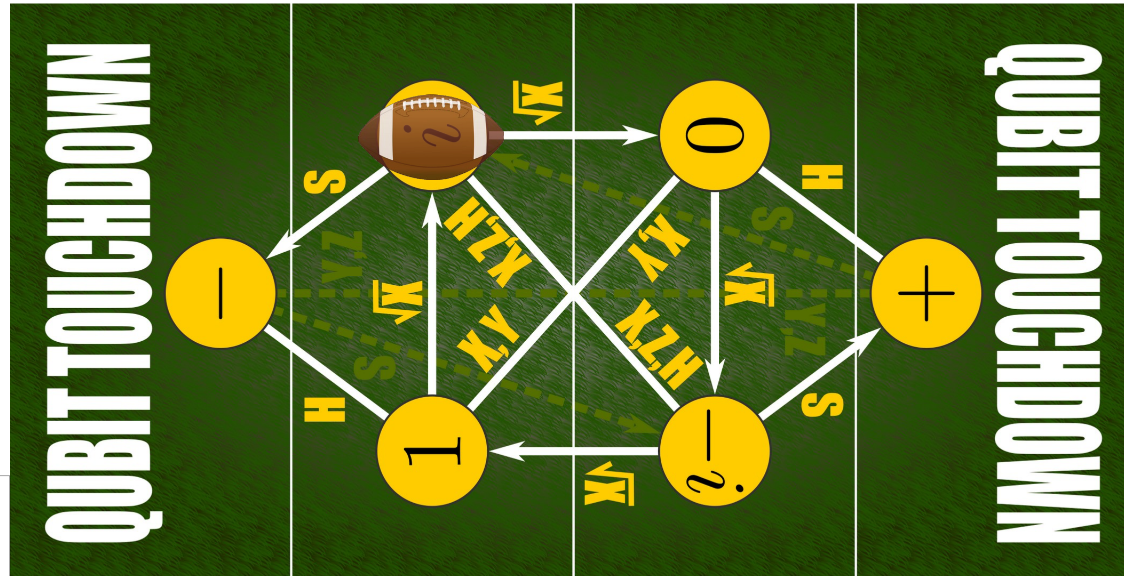
3 cards

- He draws another card.



Taylor

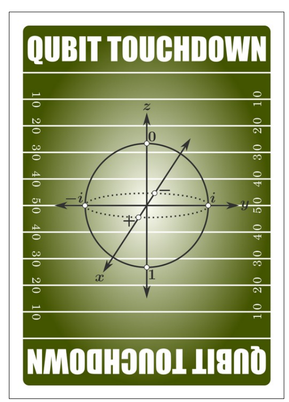
Touchdowns: 0



Ryan

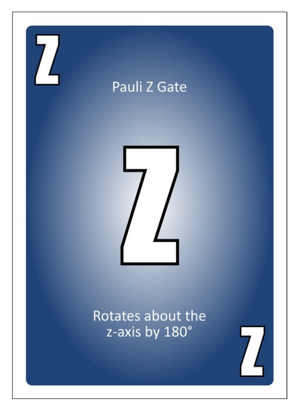
Touchdowns: 0

Draw Pile



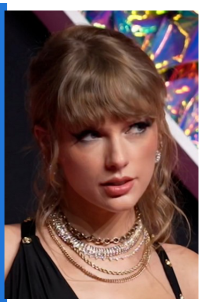
41 cards

Discard Pile



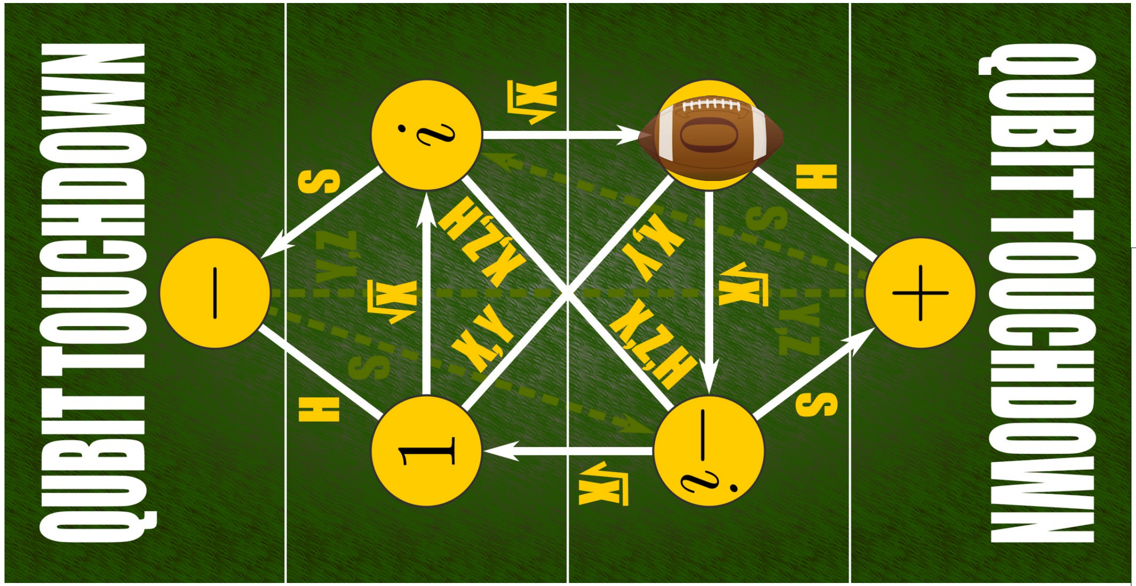
3 cards

- Taylor's turn.



Taylor

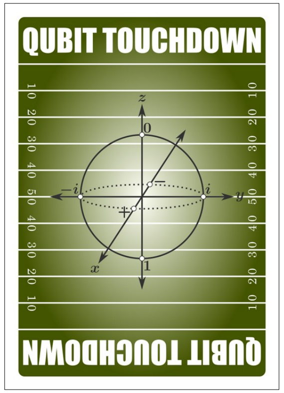
Touchdowns: 0



Ryan

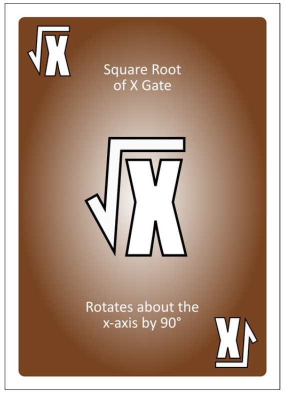
Touchdowns: 0

Draw Pile



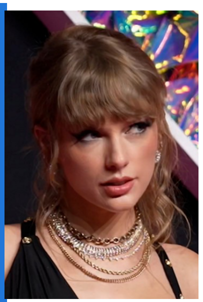
41 cards

Discard Pile



4 cards

- She plays “√X” and moves the ball to “0.”

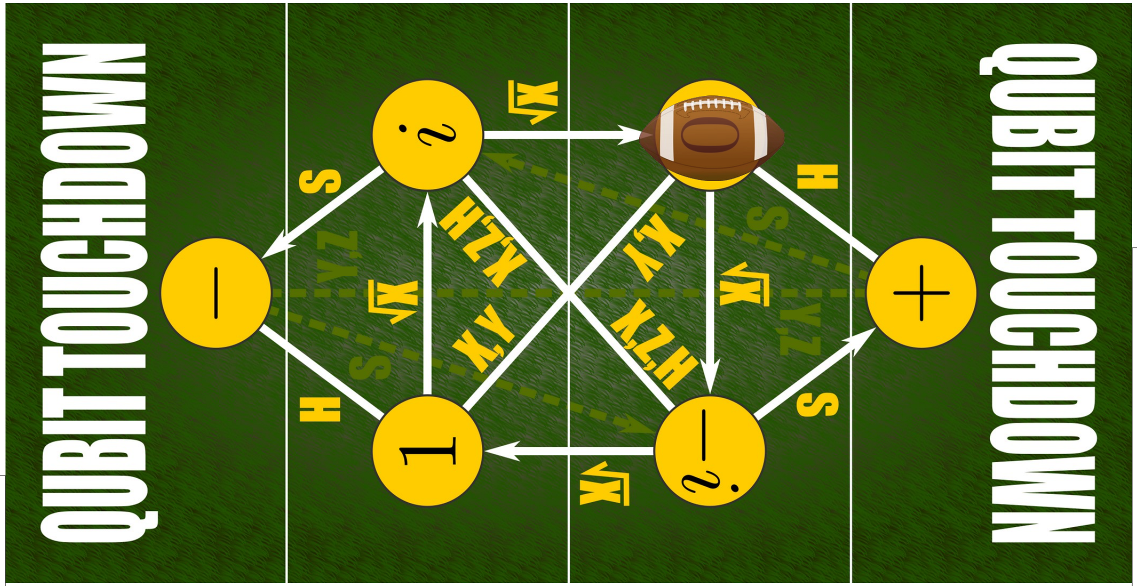


Taylor

Touchdowns: 0

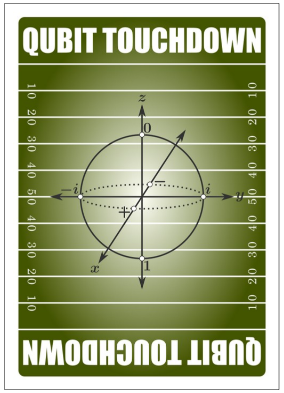
Ryan

Touchdowns: 0



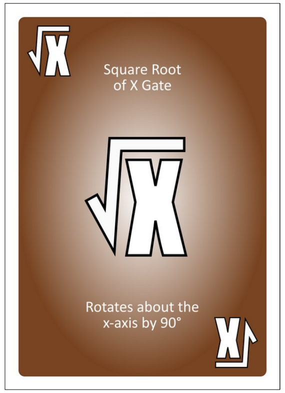
- She draws another card.

Draw Pile

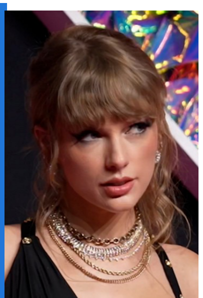


40 cards

Discard Pile

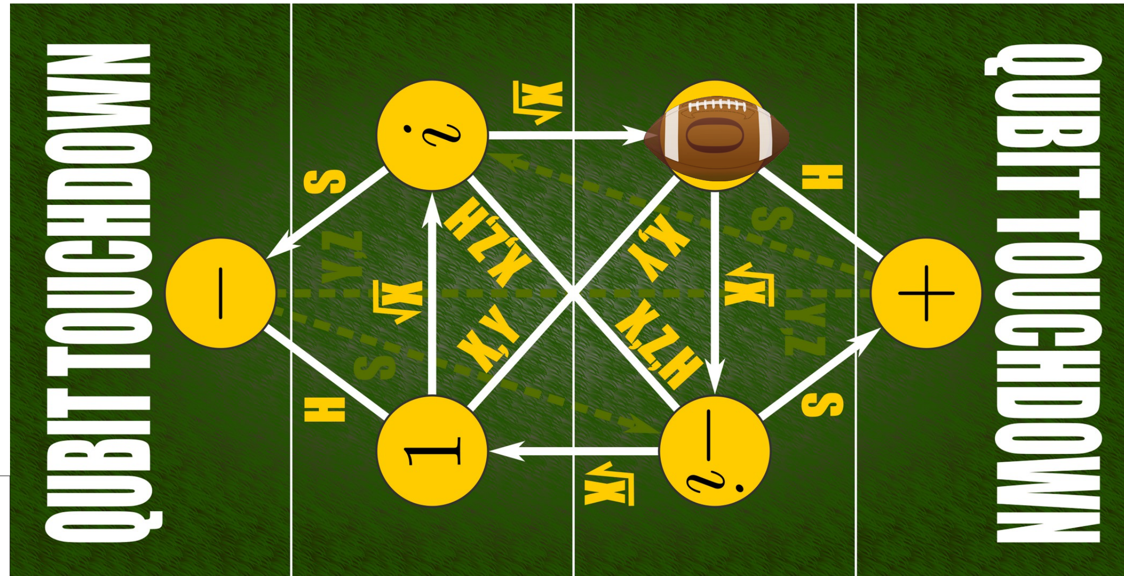


4 cards



Taylor

Touchdowns: 0

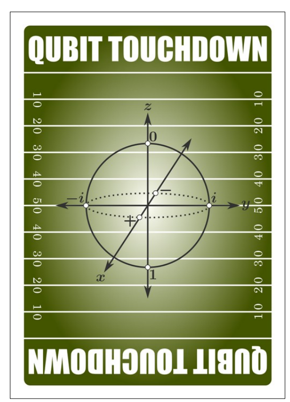


Ryan

Touchdowns: 0

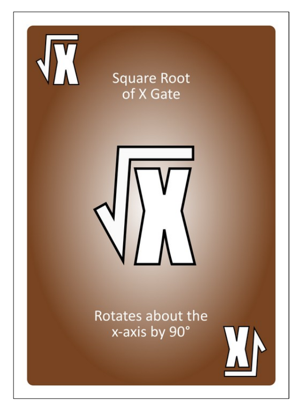
- Ryan's turn.

Draw Pile

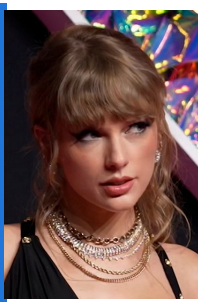


40 cards

Discard Pile

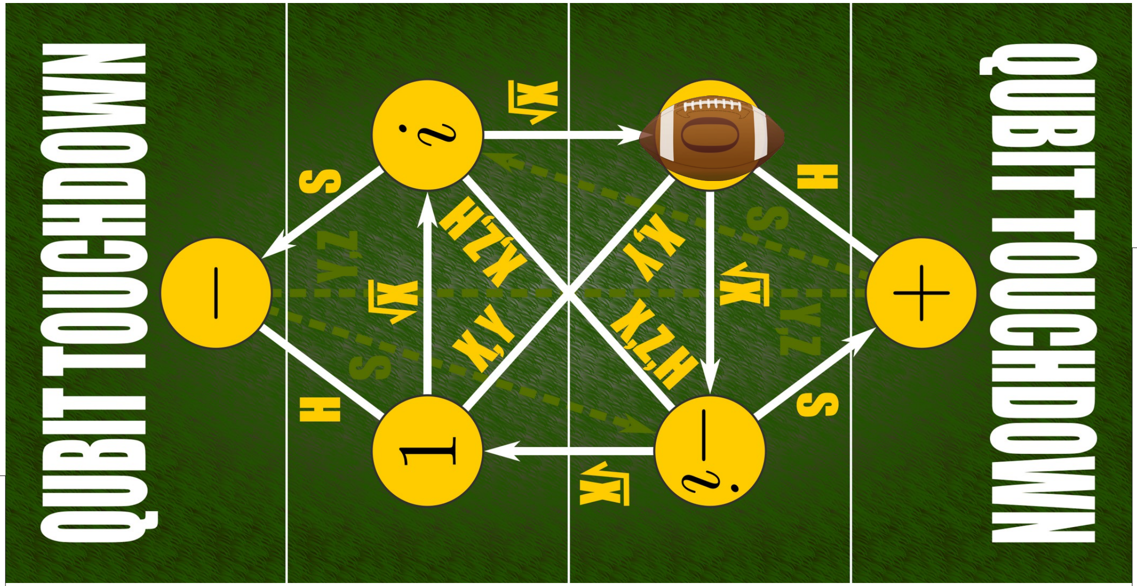


4 cards



Taylor

Touchdowns: 0

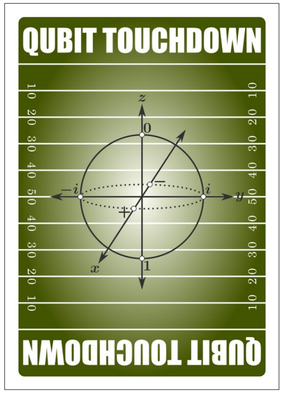


Ryan

Touchdowns: 0

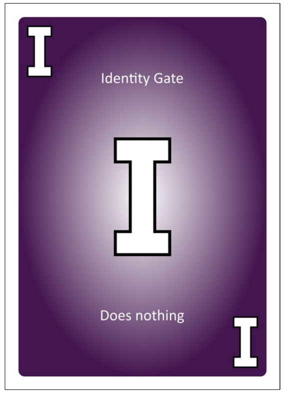
- He plays “I” and leaves the ball unmoved.

Draw Pile

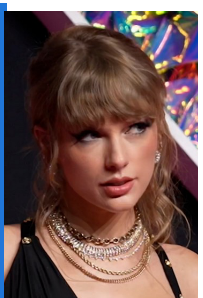


40 cards

Discard Pile



5 cards

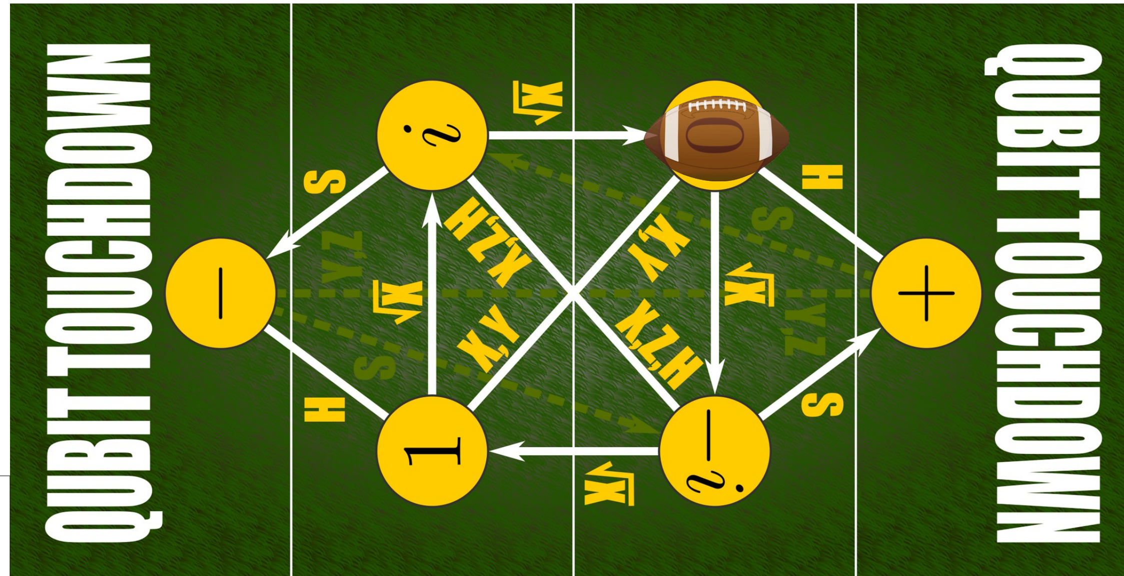


Taylor

Touchdowns: 0

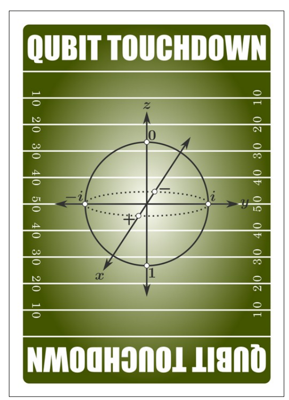
Ryan

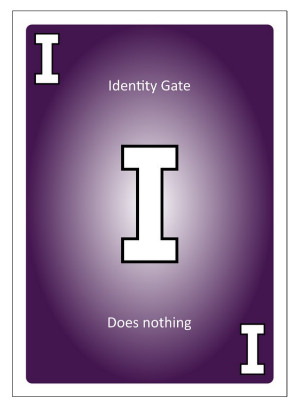
Touchdowns: 0



Draw Pile

Discard Pile

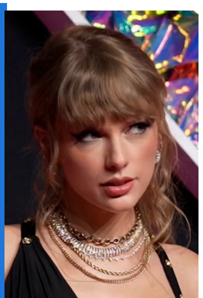




39 cards

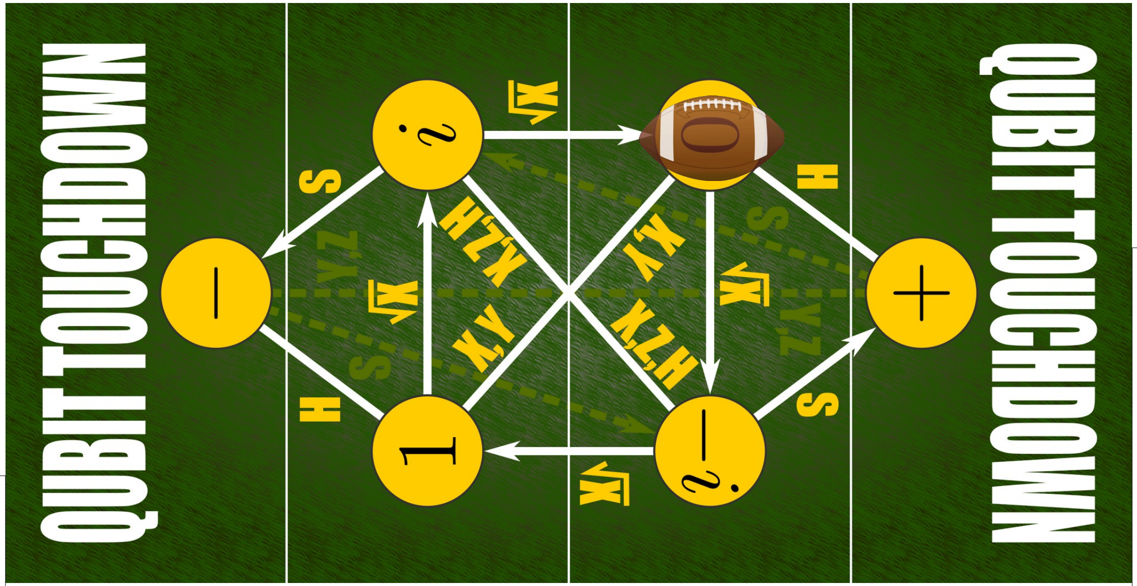
5 cards

- He draws another card.



Taylor

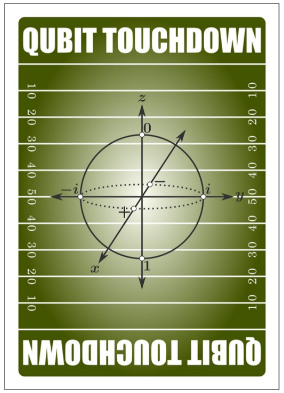
Touchdowns: 0



Ryan

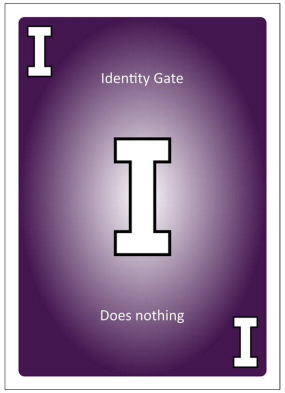
Touchdowns: 0

Draw Pile



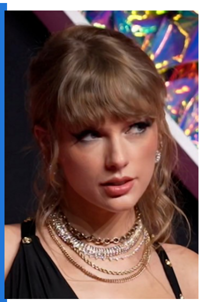
39 cards

Discard Pile



5 cards

- Taylor's turn.

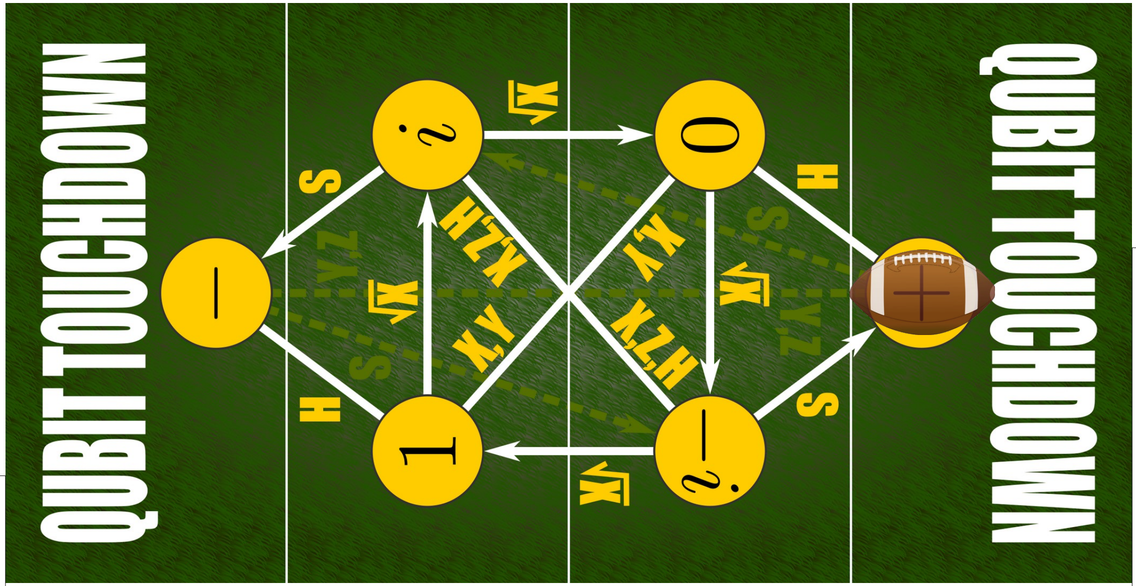


Taylor

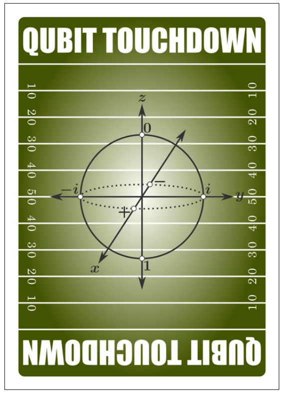
Touchdowns: 1

Ryan

Touchdowns: 0

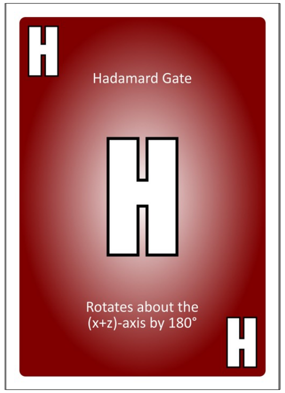


Draw Pile



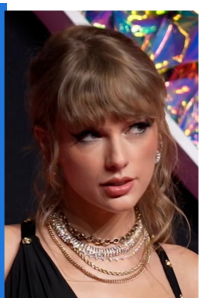
39 cards

Discard Pile



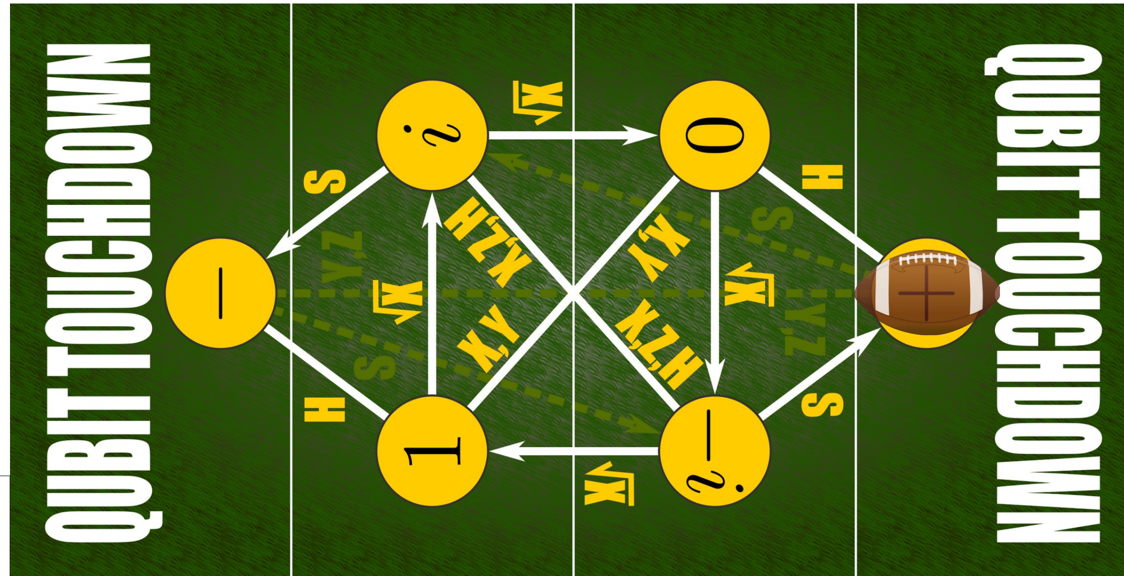
6 cards

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



Taylor

Touchdowns: 1

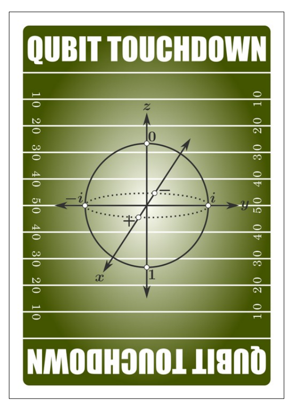


Ryan

Touchdowns: 0

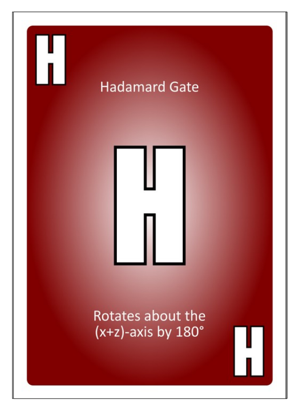
- She draws another card.

Draw Pile



38 cards

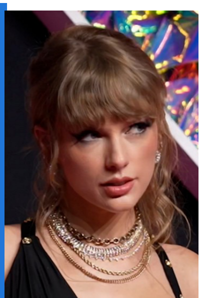
Discard Pile

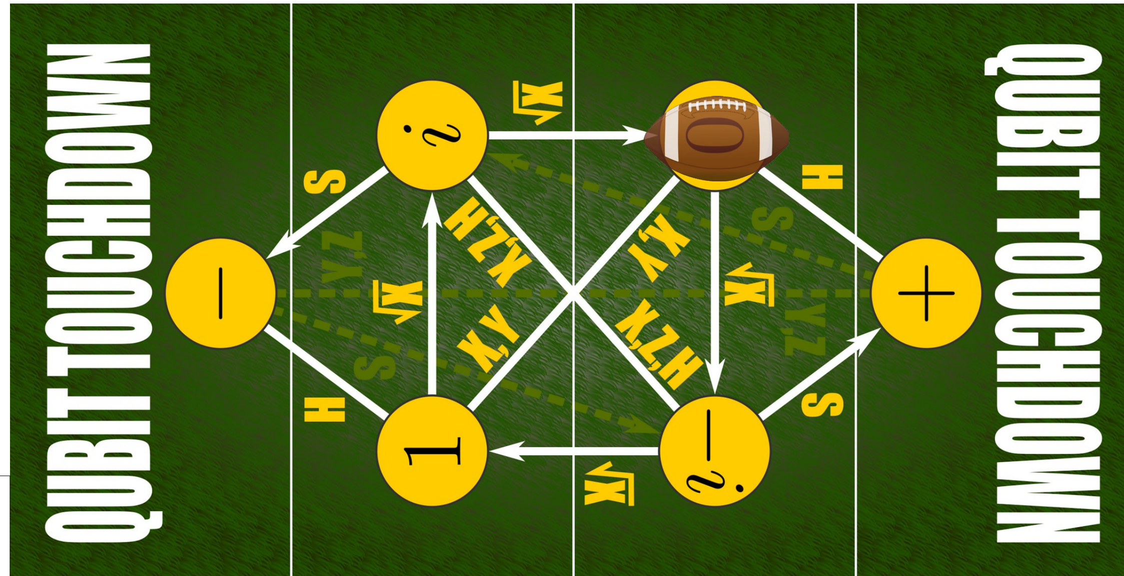


6 cards

Taylor

Touchdowns: 1

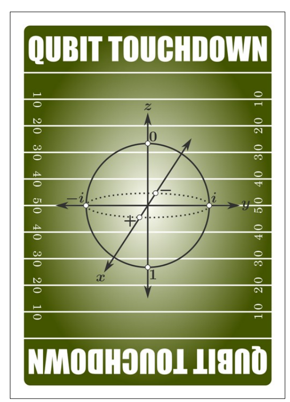




Ryan

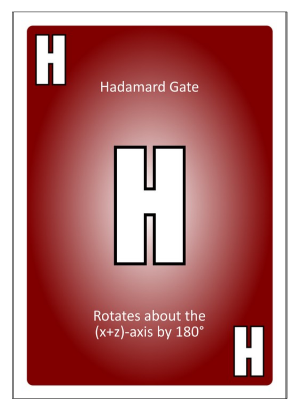
Touchdowns: 0

Draw Pile



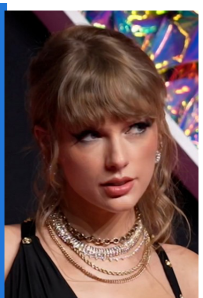
38 cards

Discard Pile



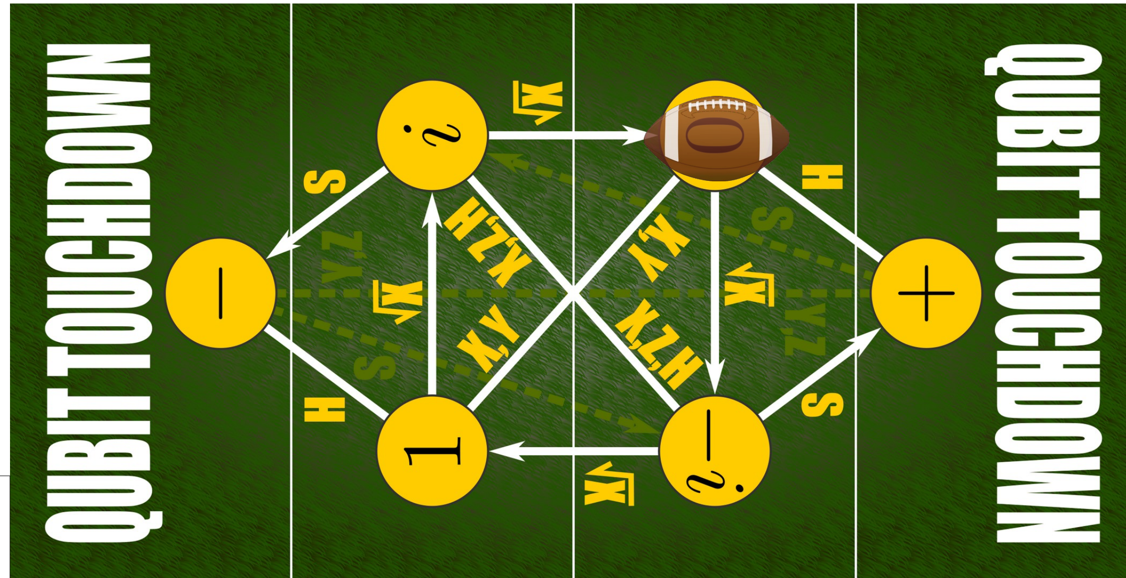
6 cards

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



Taylor

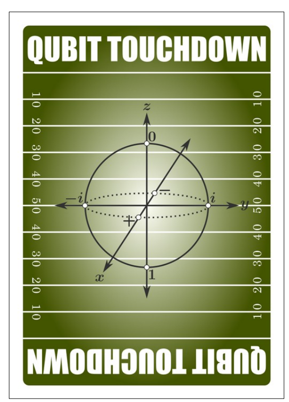
Touchdowns: 1



Ryan

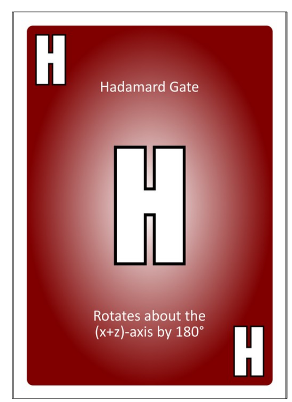
Touchdowns: 0

Draw Pile



38 cards

Discard Pile

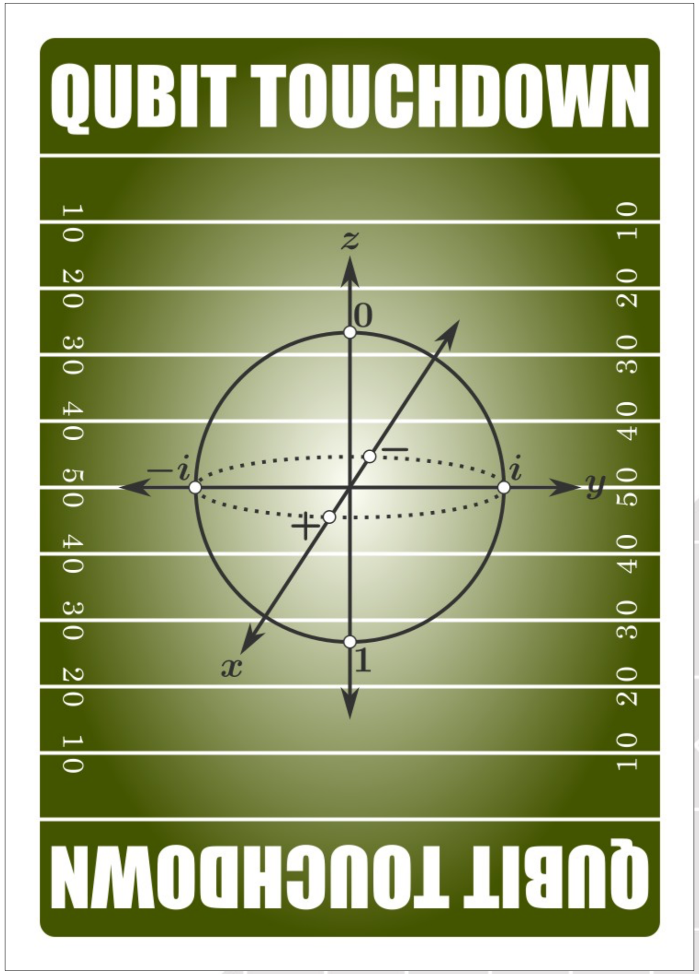


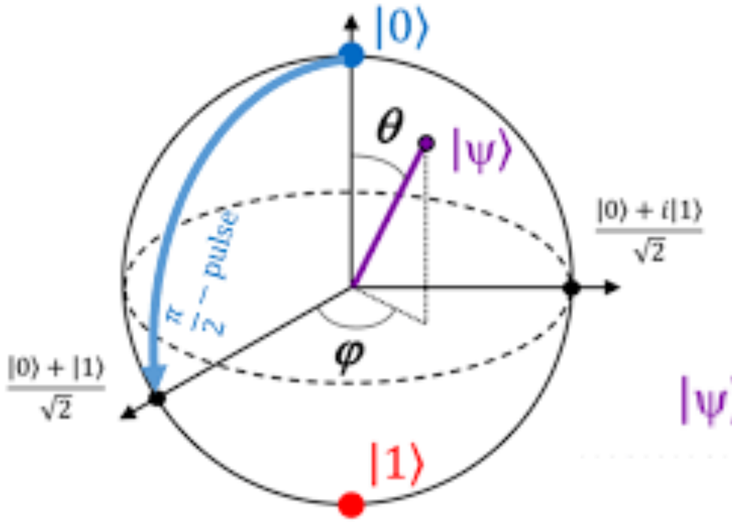
6 cards

- 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.





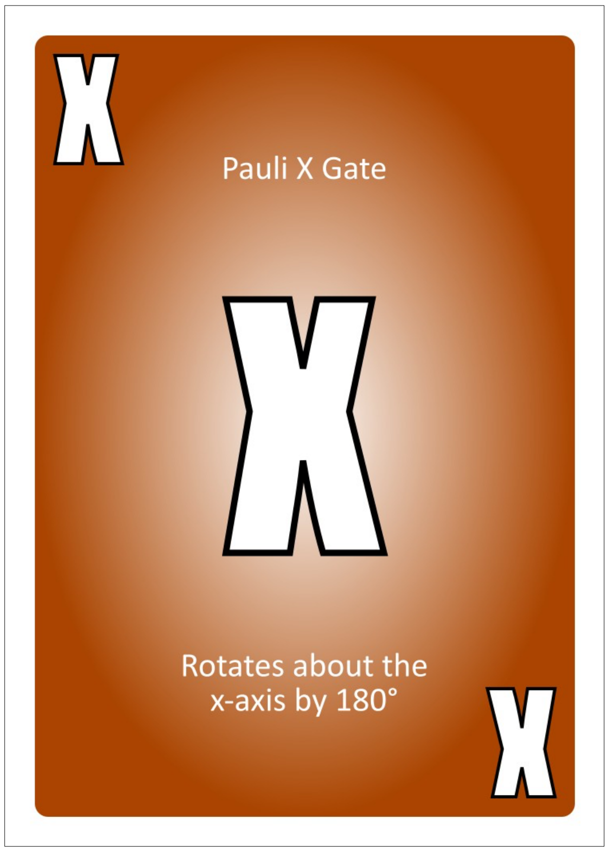
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

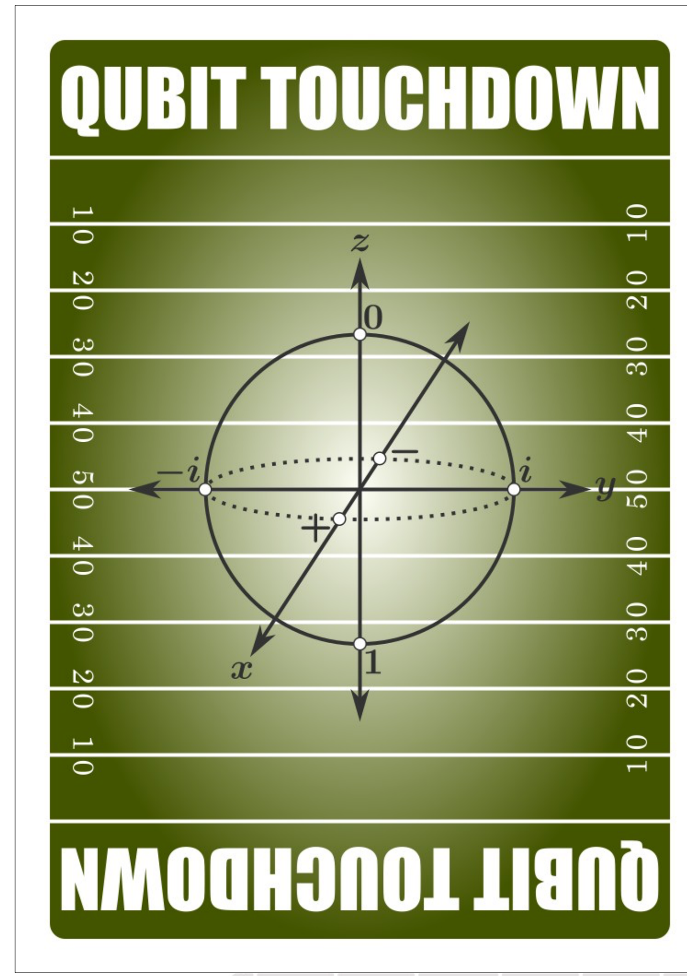
$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

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

The Physics of Qubit Touchdown

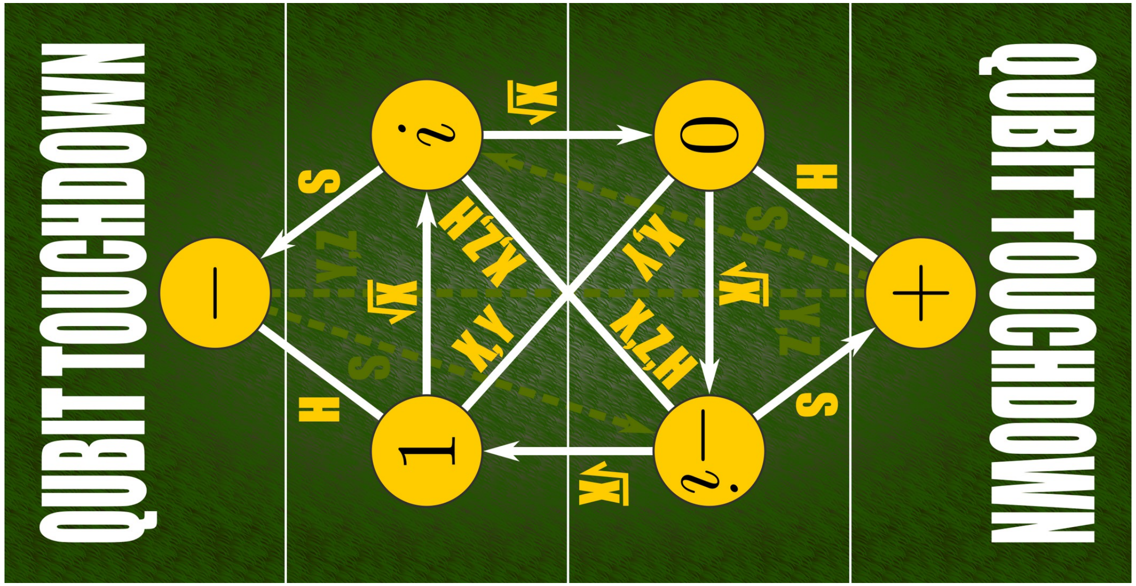
- *Quantum gates* change a qubit's state

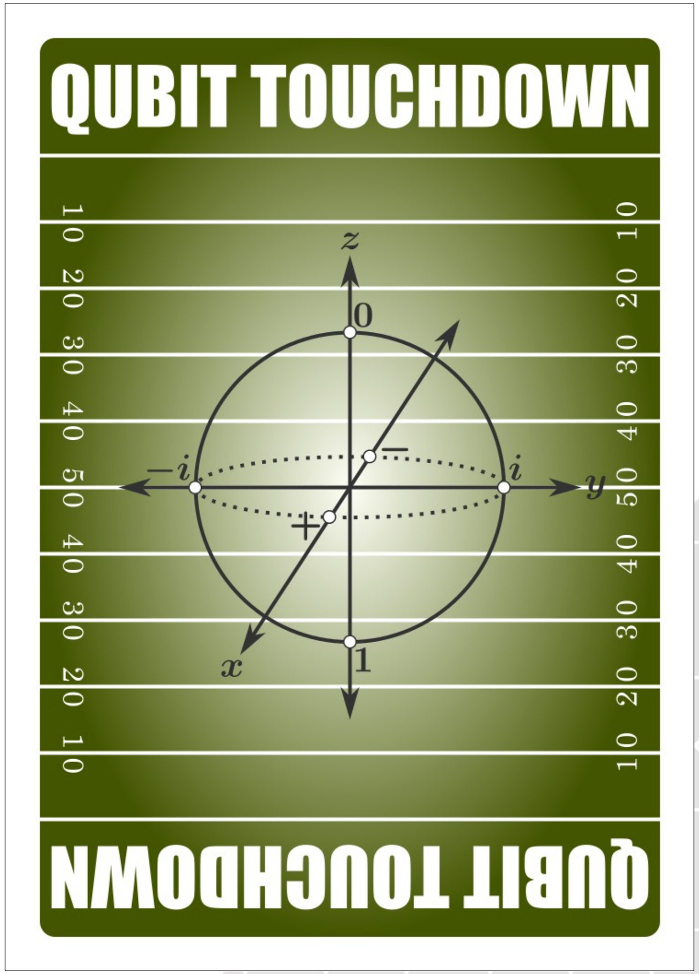




The Physics of Qubit Touchdown

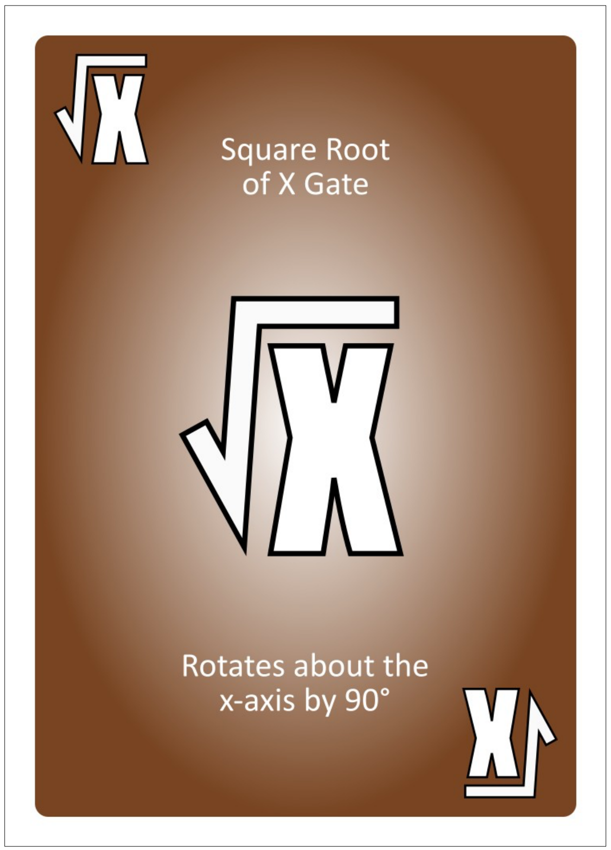
- *Quantum gates* change a qubit's state

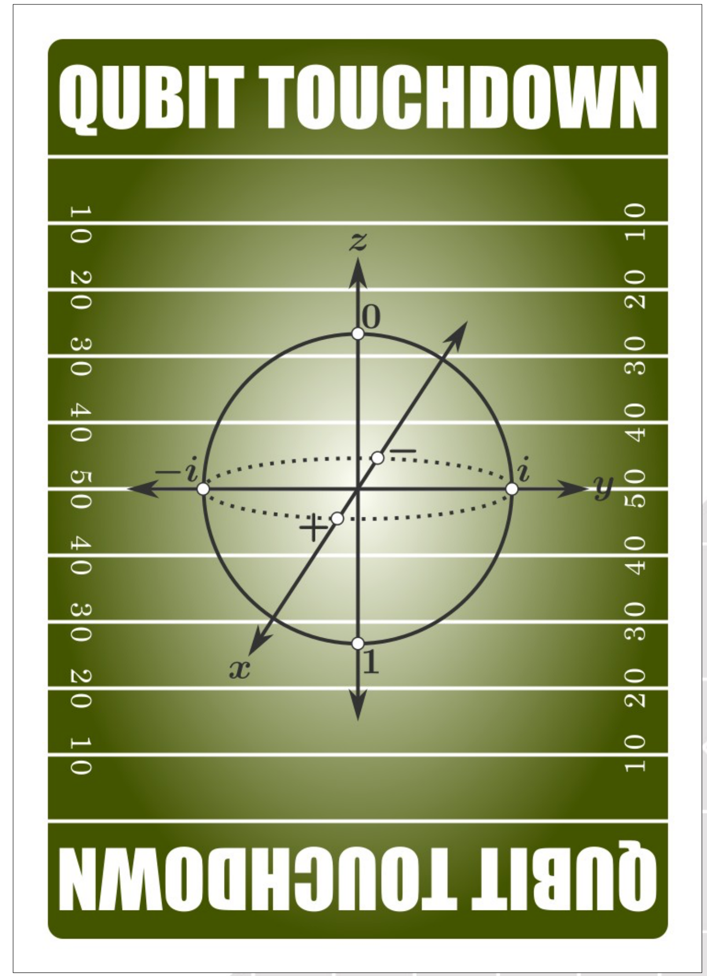




The Physics of Qubit Touchdown

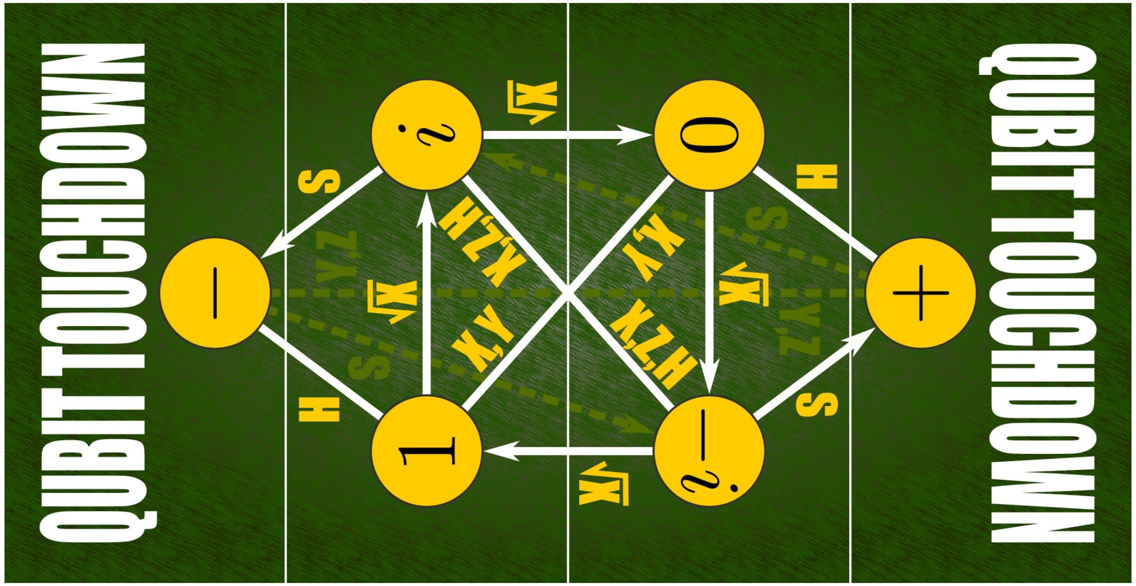
- *Quantum gates* change a qubit's state

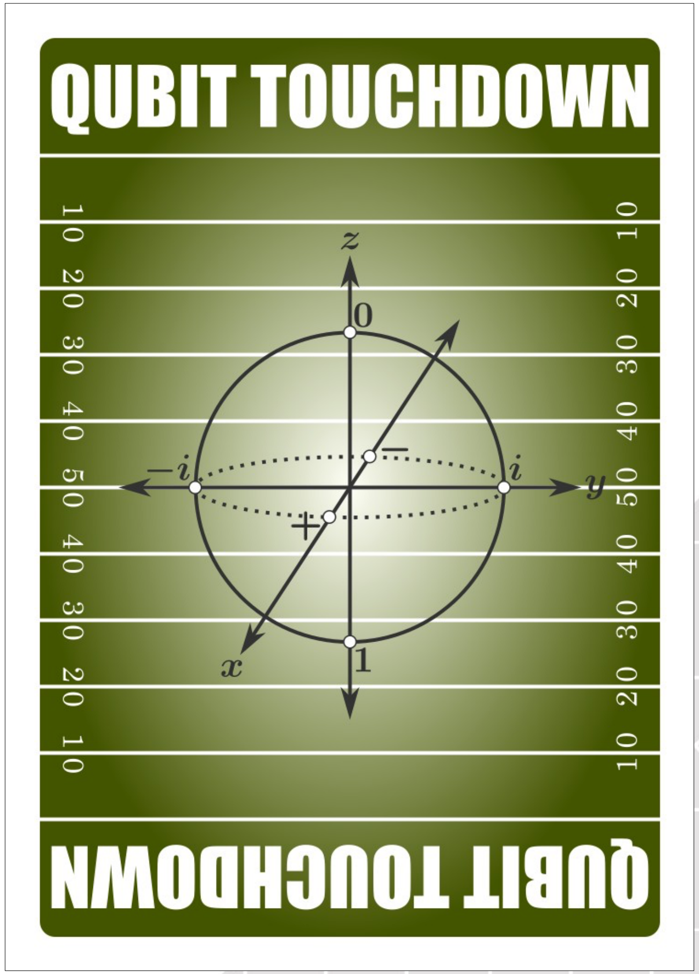




The Physics of Qubit Touchdown

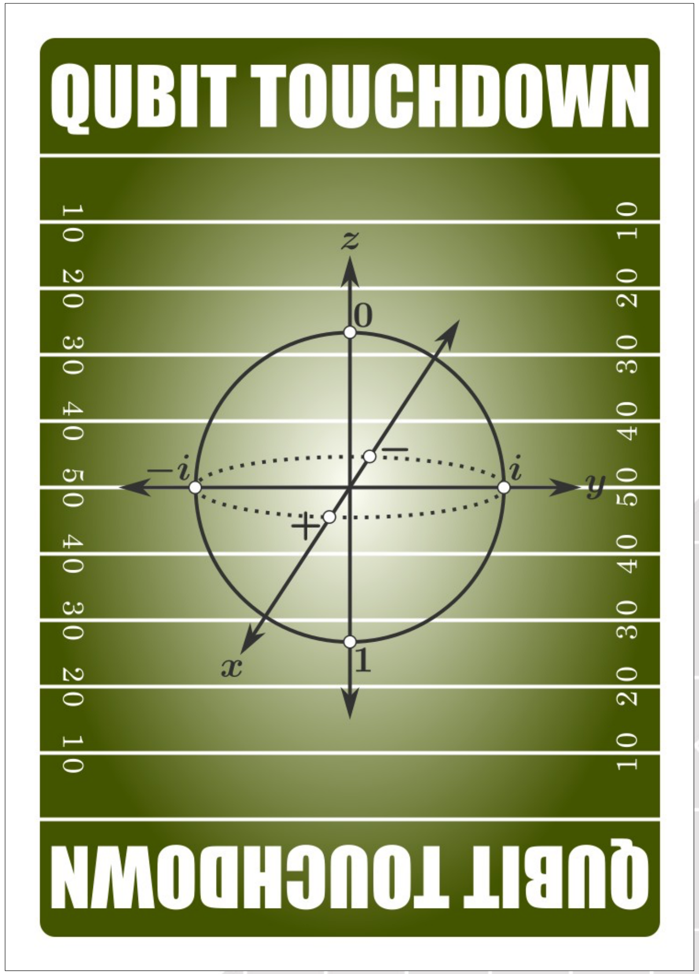
- *Quantum gates* change a qubit's state





The Physics of Qubit Touchdown

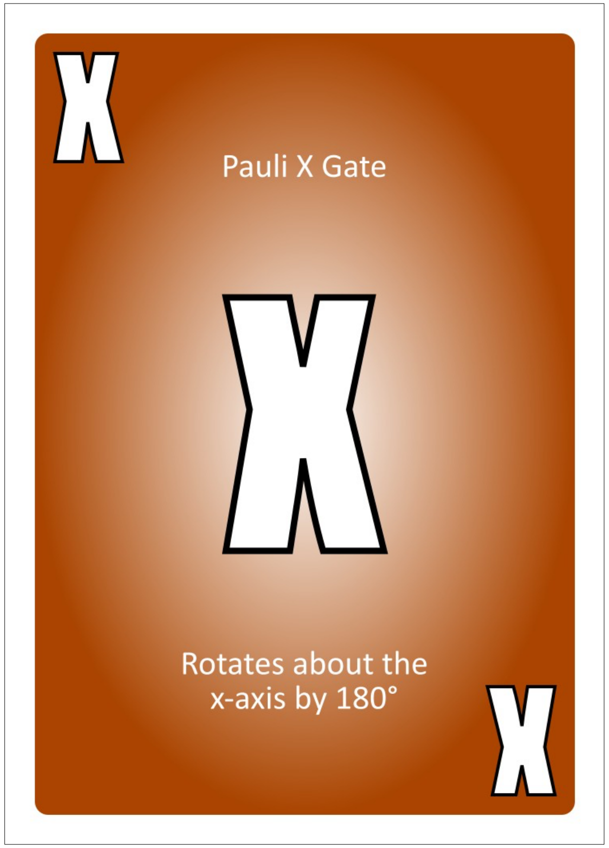
- Although a qubit can be any point on the Bloch sphere, measuring its value yields 0 or 1, each with some probability.
- Since +, –, i, –i lie on the equator, they are superpositions, or combinations, of half 0 and half 1. Measuring them yields 0 or 1, each with 50% probability.
- Kicking off after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

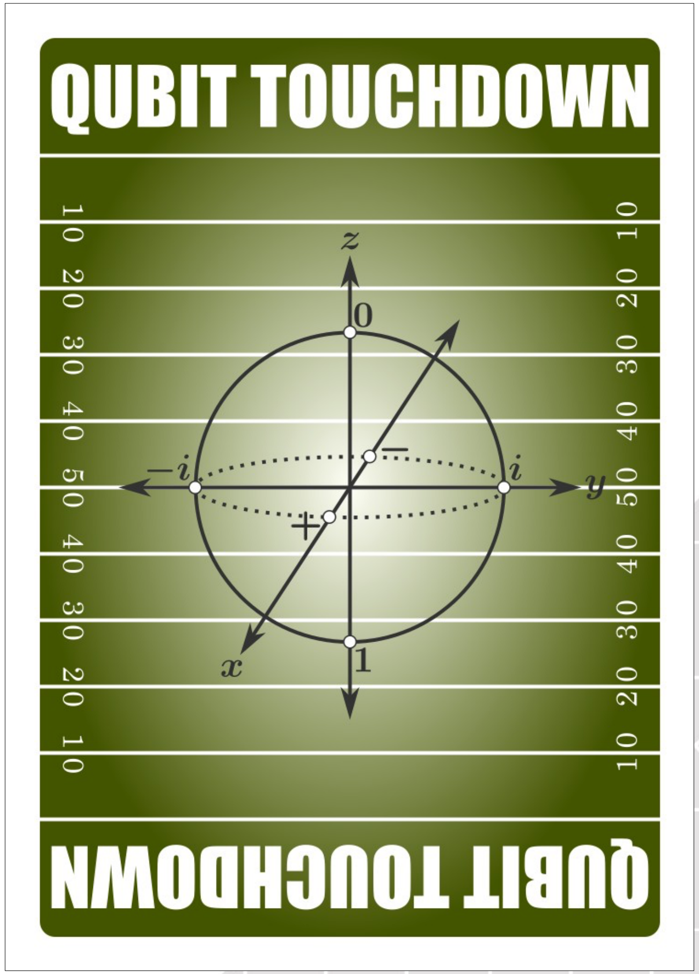


Touchdown slides are taken from Tom Wong's presentation at QIST workshop 2025

The Physics of Qubit Touchdown

- *Quantum gates* change a qubit's state

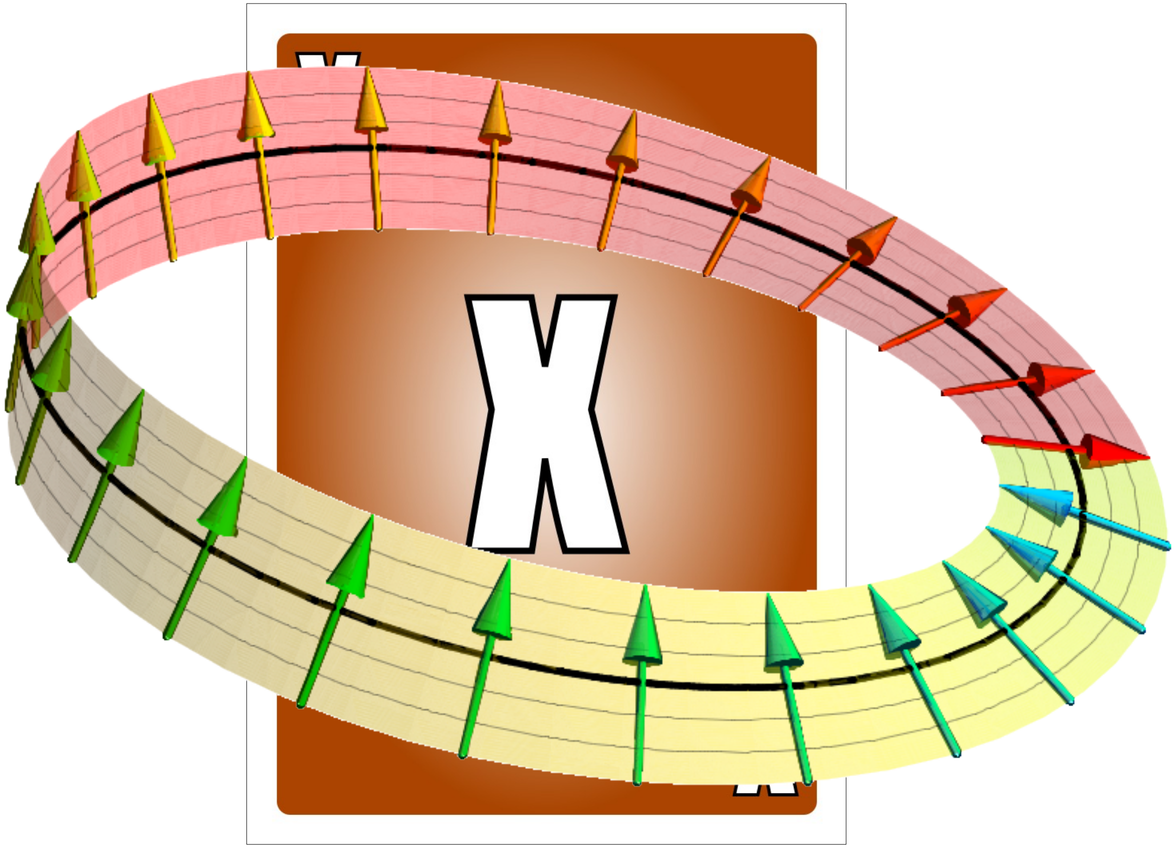


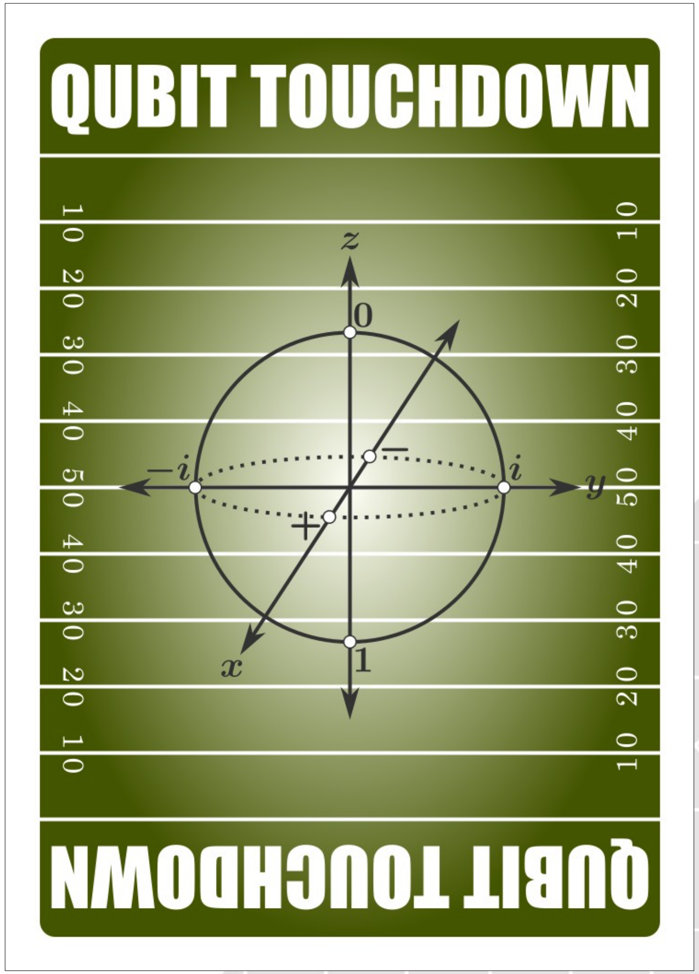


- X gate is equivalent to performing a 180-degree (or π radian) rotation around the X-axis on the Bloch sphere.
- However, 360 degree (or 2π radian) rotation introduces a global phase shift of -1 to the qubit's state vector.

The Physics of Qubit Touchdown

- *Quantum gates* change a qubit's state





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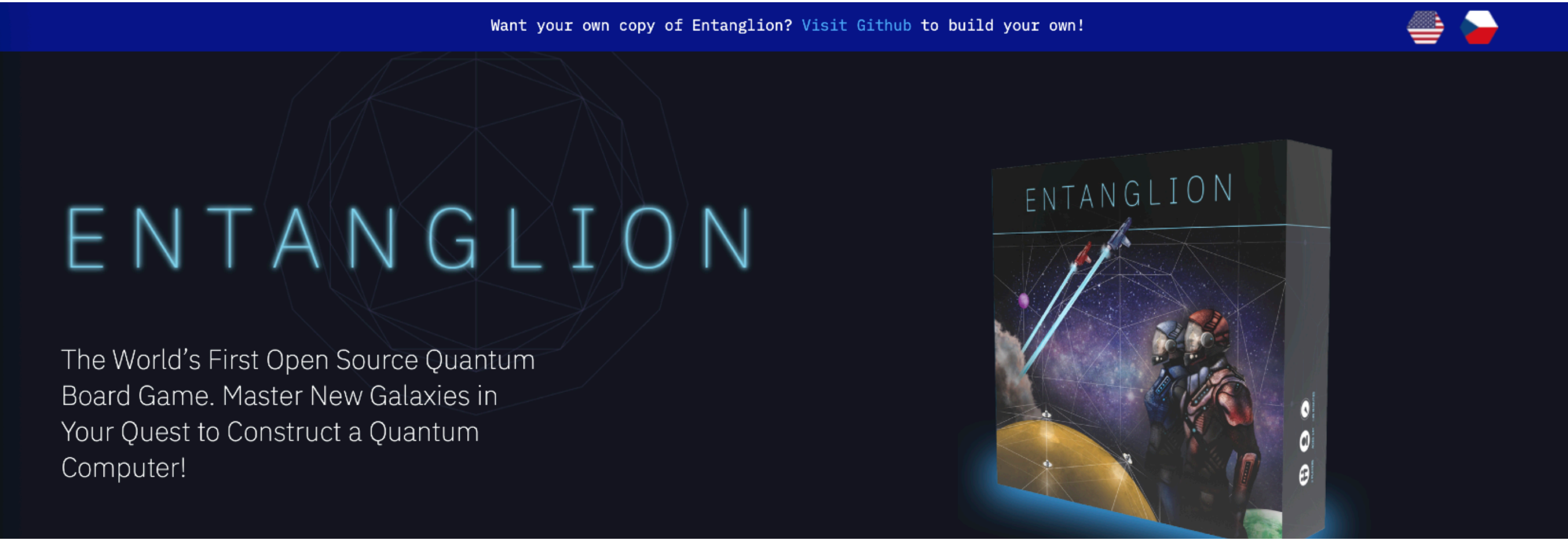
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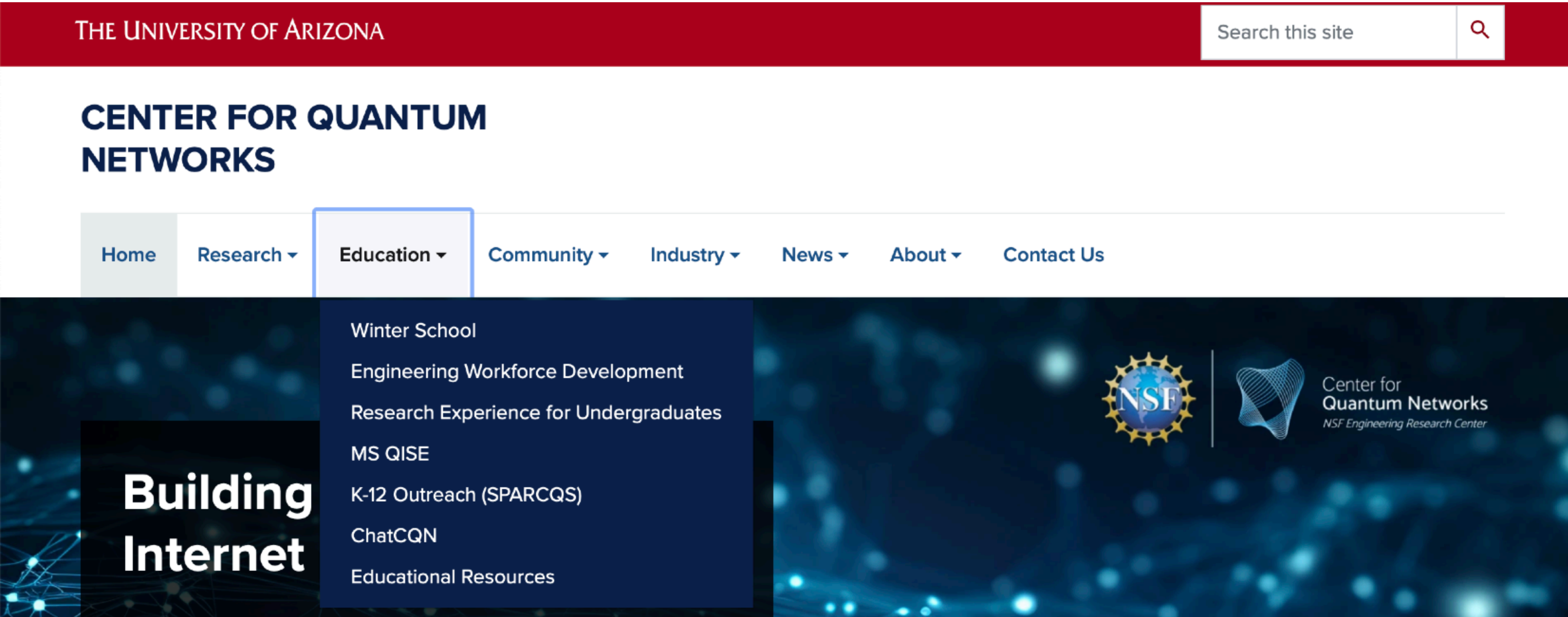
The World's First Open Source Quantum Board Game. Master New Galaxies in Your Quest to Construct a Quantum Computer!
ENTANGLION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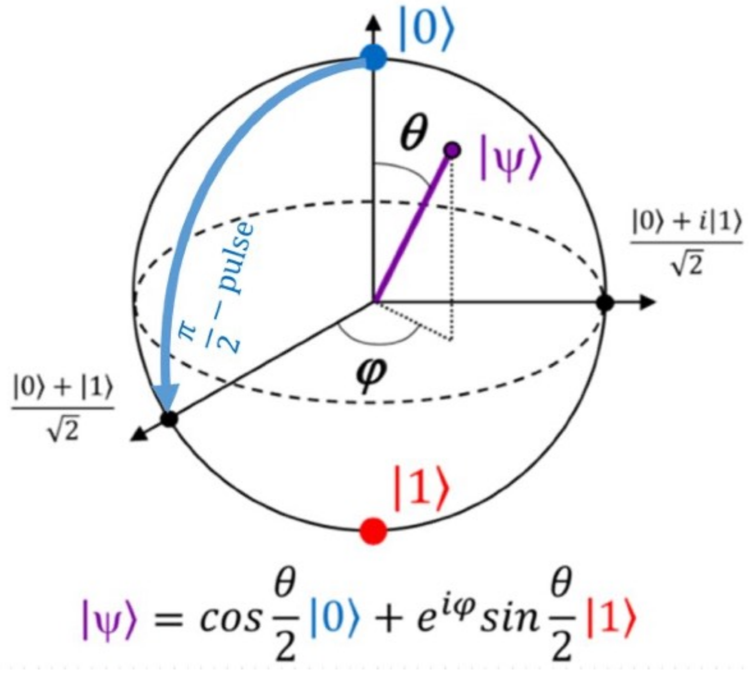
K-12 Outreach (SPARCQS)
ChatCQN
Educational Resources
Building
Internet
NSF
Center for Quantum Networks
NSF Engineering Research Center

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 ~ 3.3 million years

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

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

n $\quad 2^n$

# of Qubits	Requited Bits to Match	Equivalent Classical Computer RAM	Equivalent Classical Computer Processing Time
10	1024	128 bytes	2.6 µs
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	9.0×10^{15}	1 Terabyte	625 hours
63	9.0×10^{18}	1 Petabyte	73 years
100	9.0×10^{30}	1 Exabyte	10 trillion years
1,000	9.0×10^{301}	1.3×10^{232} Exabytes	8.5×10^{283} years

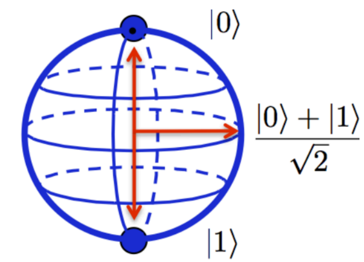
Assume we have a computer with clock speed of 4 GHz, which means it can execute 4 BILLION cycles per second.

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

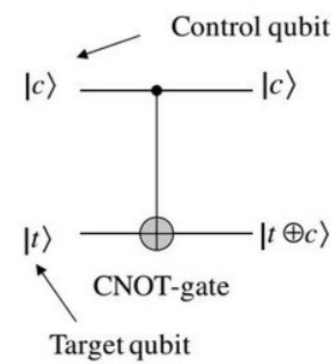
Need transition form classical to quantum:

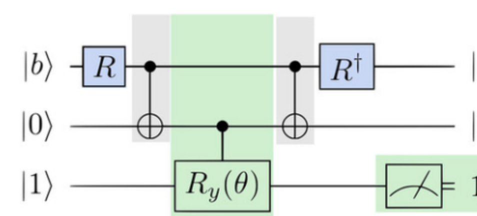
Classical Bit

Classical		Quantum
bits	⟷	qubits
gates	⟷	quantum gates
algorithms	⟷	quantum algorithms

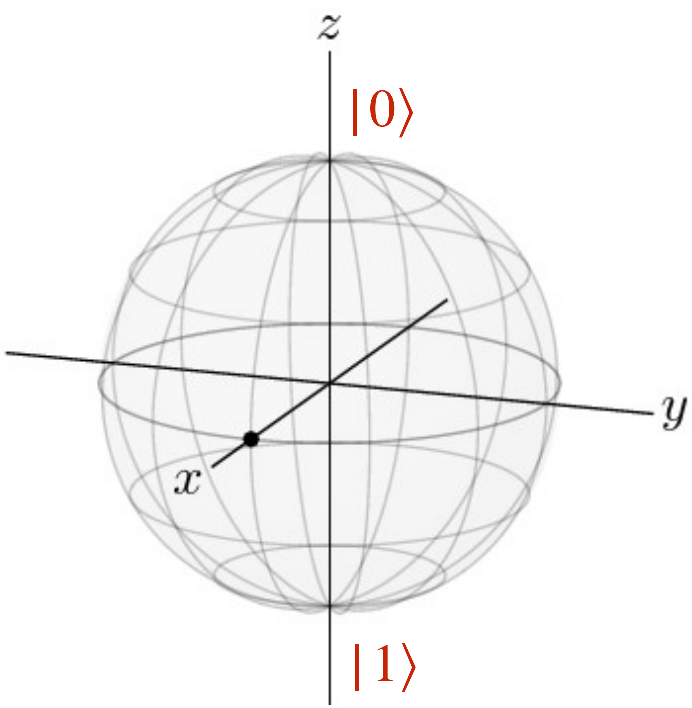


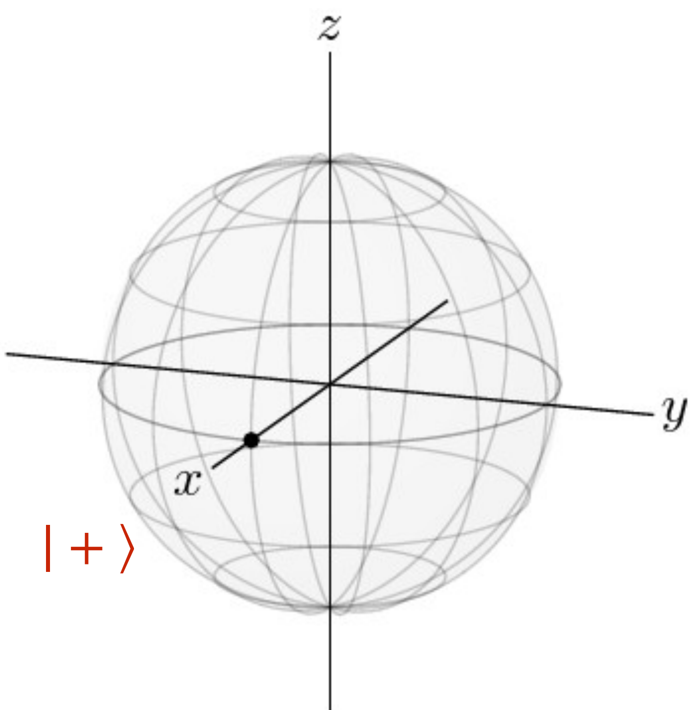
Qubit





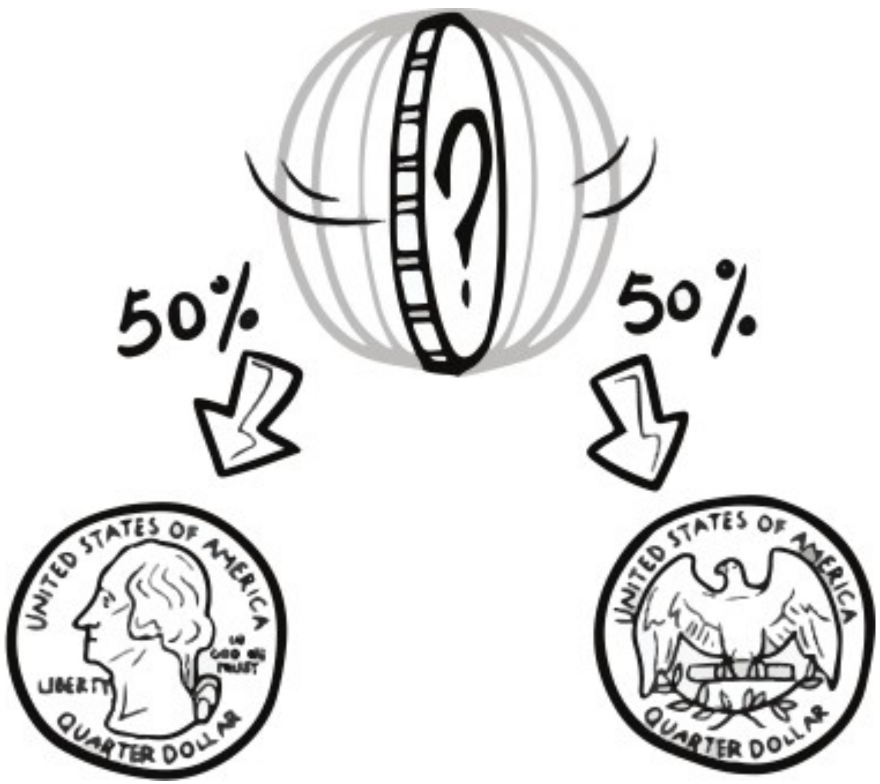
Quantum Bits (Qubits)





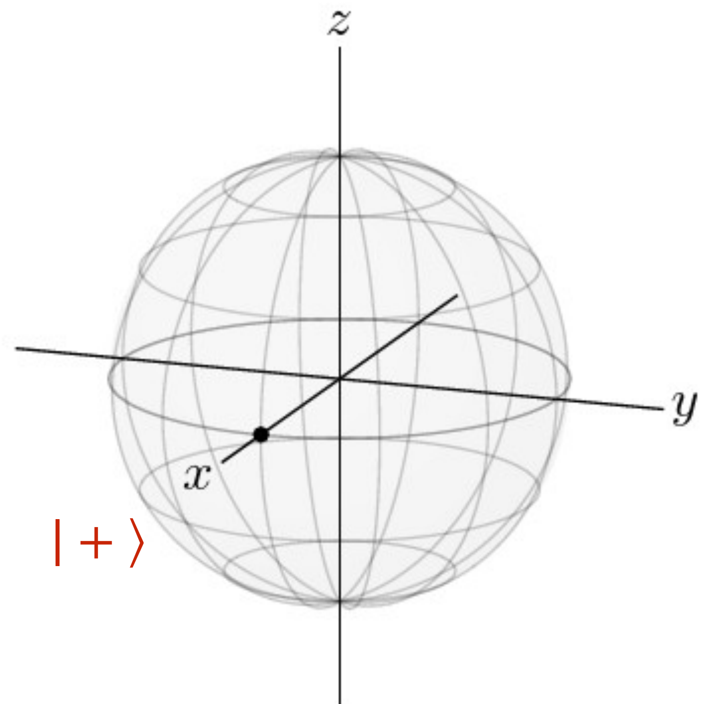
$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle = |+\rangle$$

Quantum Bits (Qubits)



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

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

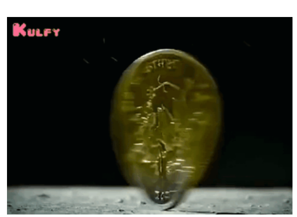


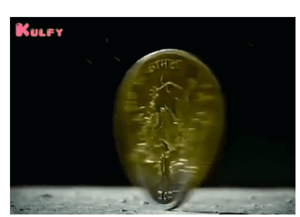
$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle = |+\rangle$$

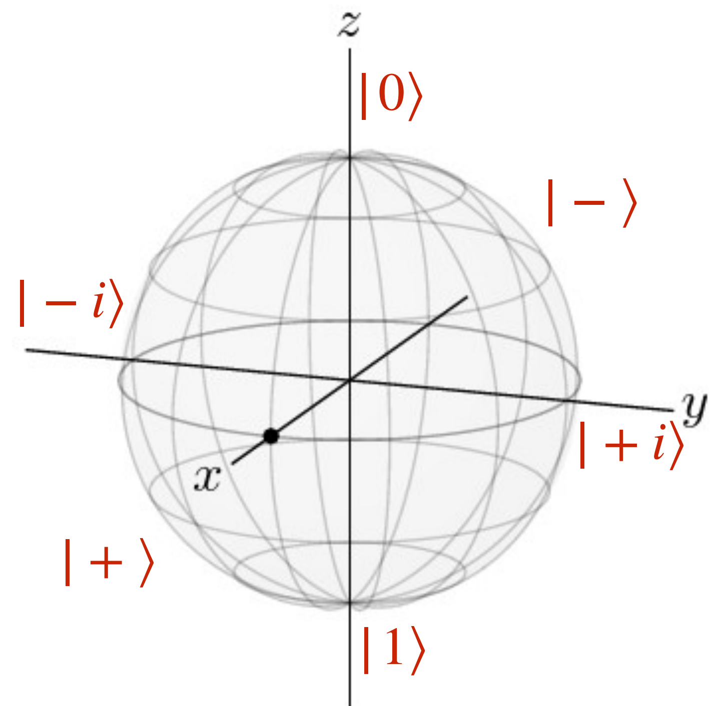
$$\left|\frac{1}{\sqrt{2}}\right|^2 = \frac{1}{2} \qquad \left|\frac{1}{\sqrt{2}}\right|^2 = \frac{1}{2}$$

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.







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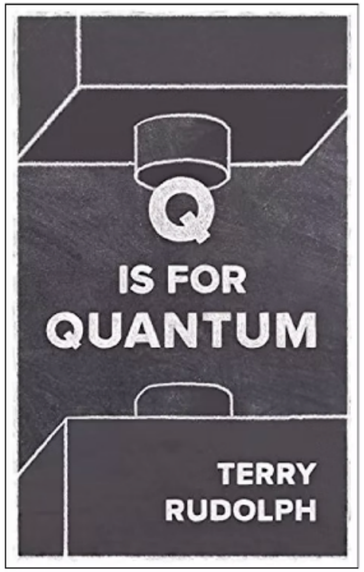

Q IS FOR QUANTUM, Terry Rudolph

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

XXXXX1

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

XXXX1X

2	3	6	7	10	11	14	15
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XXX1XX

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XX1XXX

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X1XXXX

32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47
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1XXXXX

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

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In base 2: 101011

Suppose your number was 43

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56	57	58	59	60	61	62	63

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

Suppose your number was 43

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33	35	37	39	41	43	45	47
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48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63

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 $x \cdot s = x_0 s_0 + \cdots + x_{n-1} s_{n-1} = \sum_{i=0}^{n-1} x_i s_i \pmod 2$. Find the unknown string $s = (s_0 s_1 \cdots s_{n-1})$.
- Best classical algorithm uses $\mathcal{O}(n)$ calls to $f_s(x) = x \cdot s \mod 2$. Each query gives one bit of information of s (because f outputs one bit).

- How do we find s with less than n queries? → Use superposition (over all possible input bit strings)

Inner Product

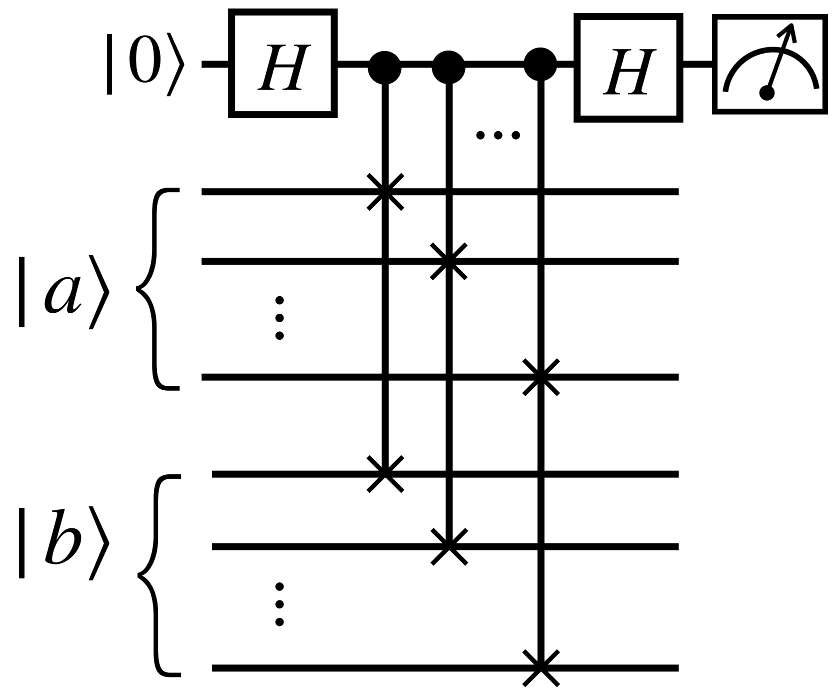
$\vec{a} = (a_1, a_2, \cdots, a_{1024})$

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

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

How many operations

= 1024 multiplications + 1023 additions



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

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

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

$2^{10} = 1024$

12 operations are needed.

Using vector notation

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

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

$$\vec{a}\cdot\vec{b} = \frac{1}{\sqrt{2}}\cdot 1 + \frac{1}{\sqrt{2}}\cdot 0$$

$$= \frac{1}{\sqrt{2}} \approx 0.707$$

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

Using Dirac bracket notation

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

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

$$\langle a|b\rangle = \frac{1}{\sqrt{2}}\cdot 1 + \frac{1}{\sqrt{2}}\cdot 0$$

$$= \frac{1}{\sqrt{2}} \approx 0.707$$

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

IBM Quantum Composer

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

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,[1] Avinatan Hassidim,[2] and Seth Lloyd[3]

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[2]*Research Laboratory for Electronics, MIT, Cambridge, Massachusetts 02139, USA*
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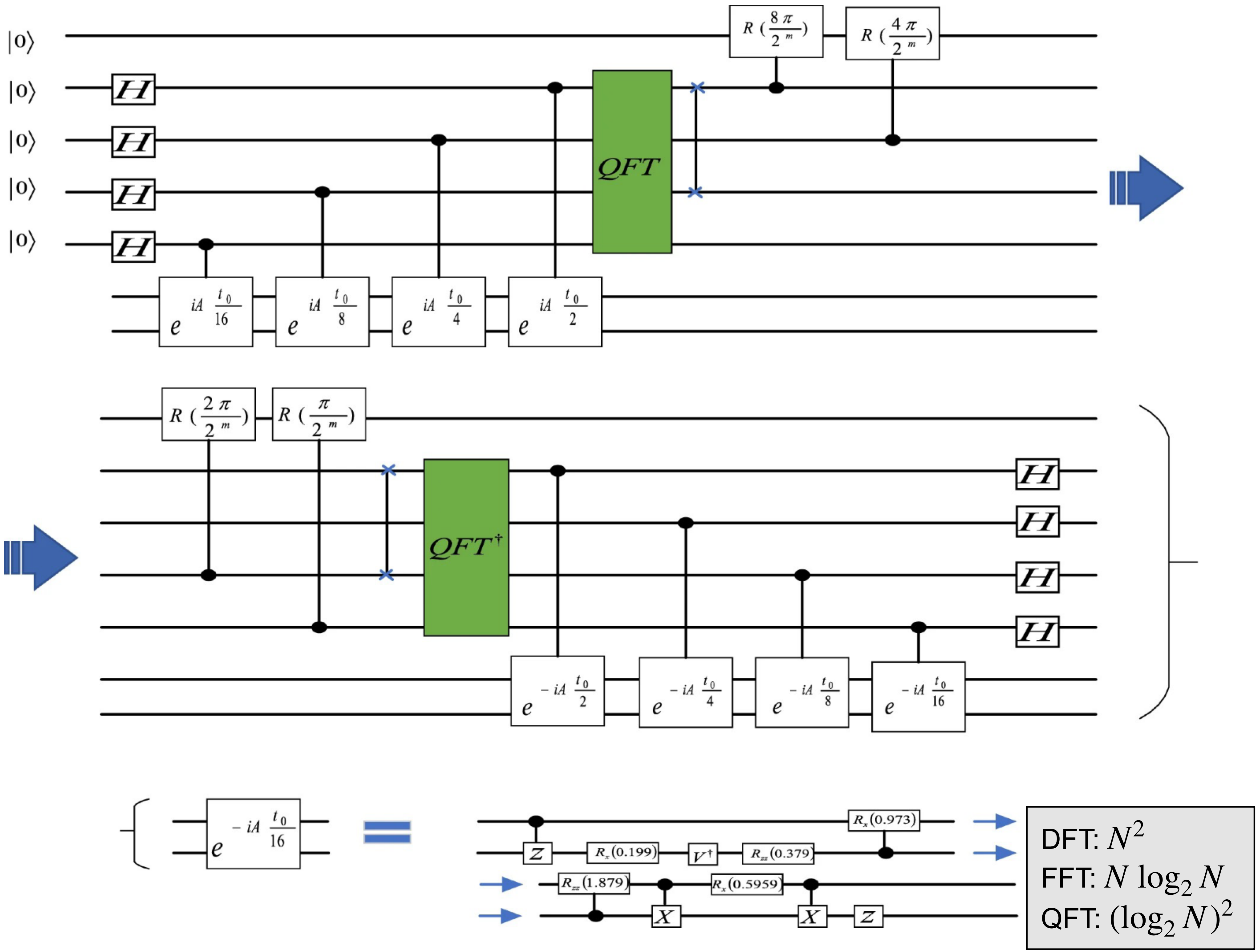
(Received 5 July 2009; published 7 October 2009)

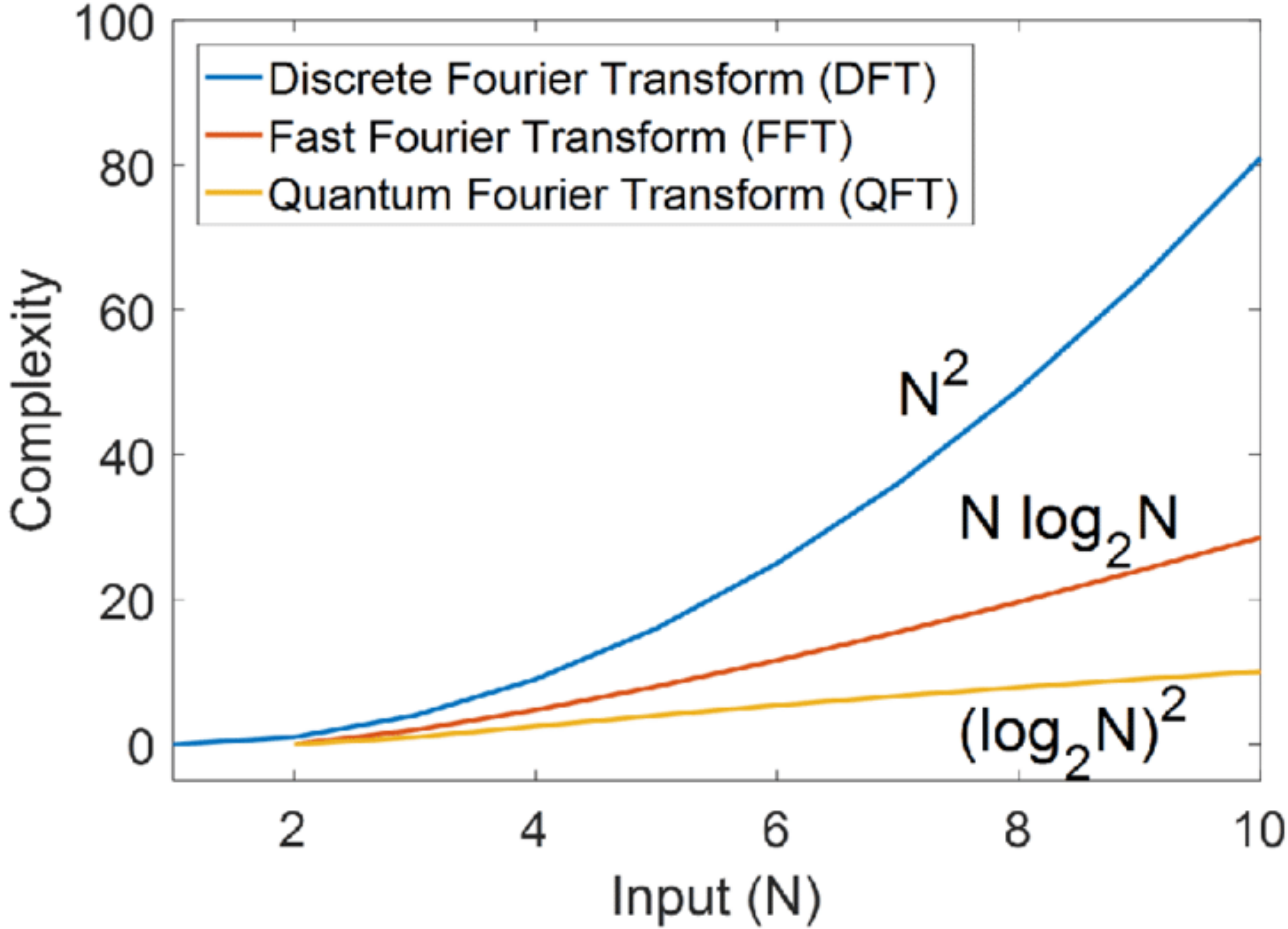
Solving linear systems of equations is a common problem that arises both on its own and as a subroutine in more complex problems: given a matrix A and a vector $\vec{b}$, find a vector $\vec{x}$ such that $A\vec{x} = \vec{b}$. We consider the case where one does not need to know the solution $\vec{x}$ 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 κ, 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 κ. Indeed, for small values of κ [i.e., 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=$O(N)$


|0⟩
H
QFT
$R(\frac{8\pi}{2^m})$
$R(\frac{4\pi}{2^m})$
$e^{iA\frac{t_0}{16}}$
$e^{iA\frac{t_0}{8}}$
$e^{iA\frac{t_0}{4}}$
$e^{iA\frac{t_0}{2}}$
$R(\frac{2\pi}{2^m})$
$R(\frac{\pi}{2^m})$
$QFT^\dagger$
$e^{-iA\frac{t_0}{2}}$
$e^{-iA\frac{t_0}{4}}$
$e^{-iA\frac{t_0}{8}}$
$e^{-iA\frac{t_0}{16}}$
Z
$R_x(0.199)$
$V^\dagger$
$R_{zz}(0.379)$
$R_x(0.973)$
$R_{zz}(1.879)$
X
$R_x(0.5959)$
DFT: N^2
FFT: $N \log_2 N$
QFT: $(\log_2 N)^2$



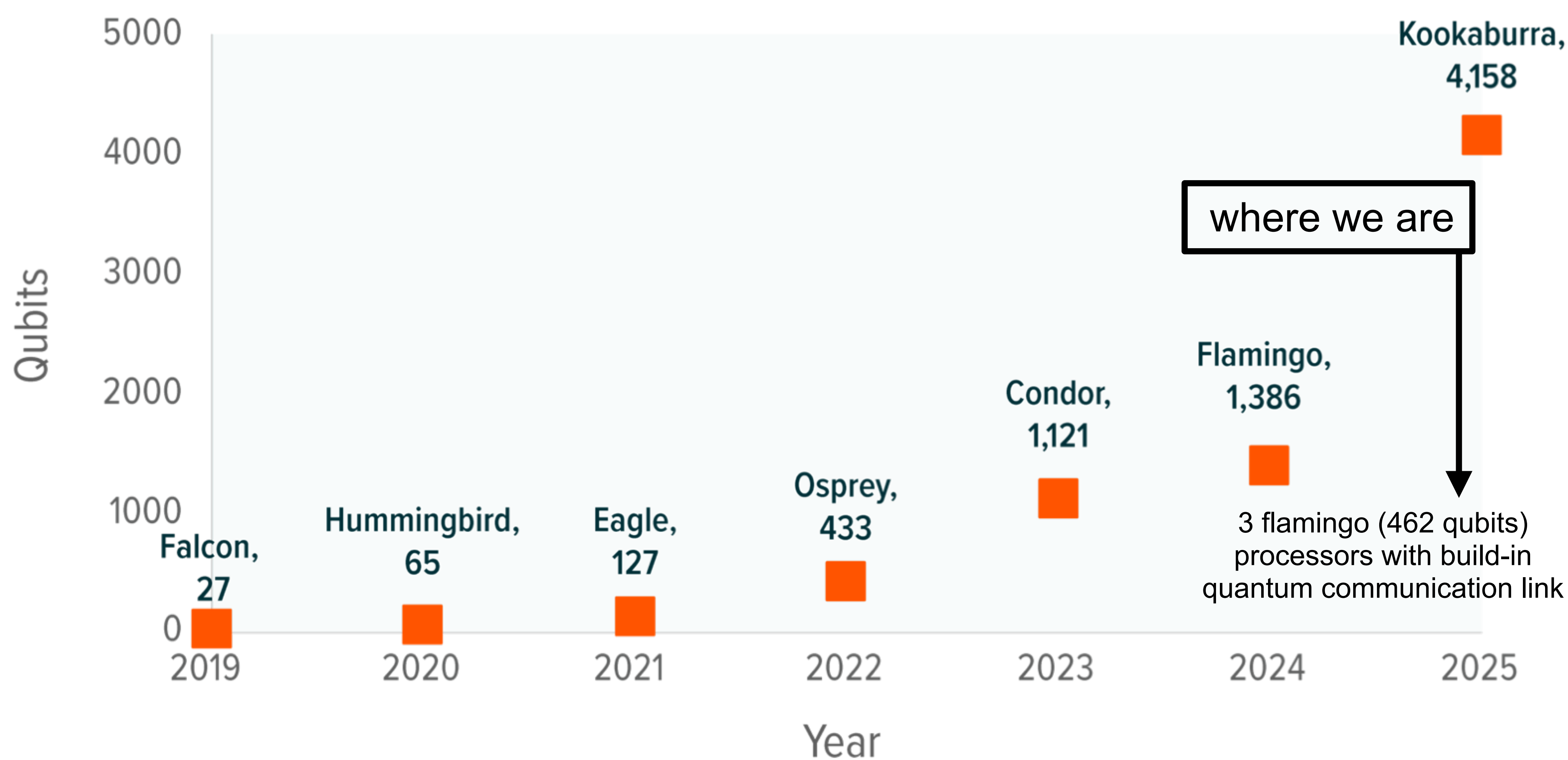
100
80
60
40
20
0
2
4
6
8
10
Complexity
Input (N)
Discrete Fourier Transform (DFT)
Fast Fourier Transform (FFT)
Quantum Fourier Transform (QFT)
N^2
N log_2N
(log_2N)^2

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

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

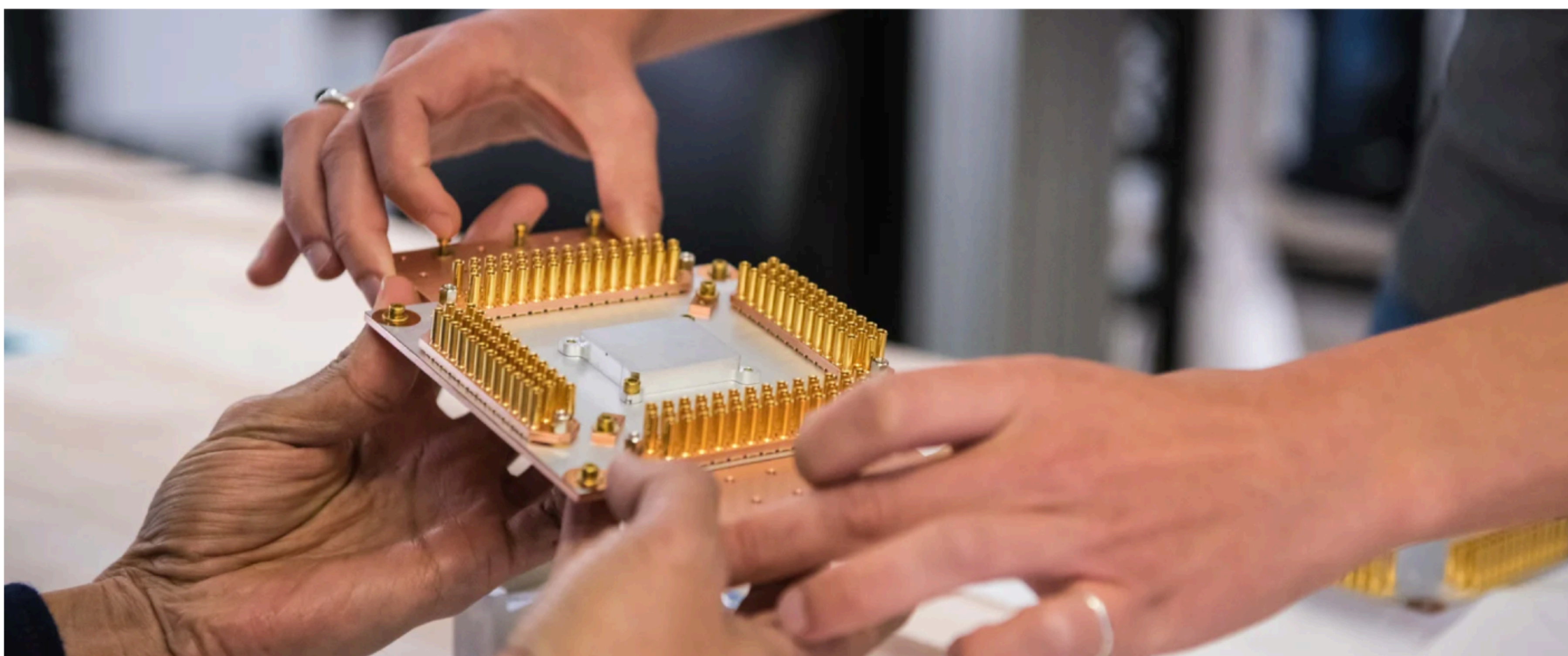
The commitment, to be signed May 21 on the sidelines of the G7 and U.S.-Japan Leaders' Meeting, aims to advance development of a fault-tolerant quantum computer by supporting research, entrepreneurship and workforce training.

May 17, 2023 · 2 min read

C Charina Chou
Director and COO,
Google Quantum AI

H Hartmut Neven
VP, Google Quantum AI

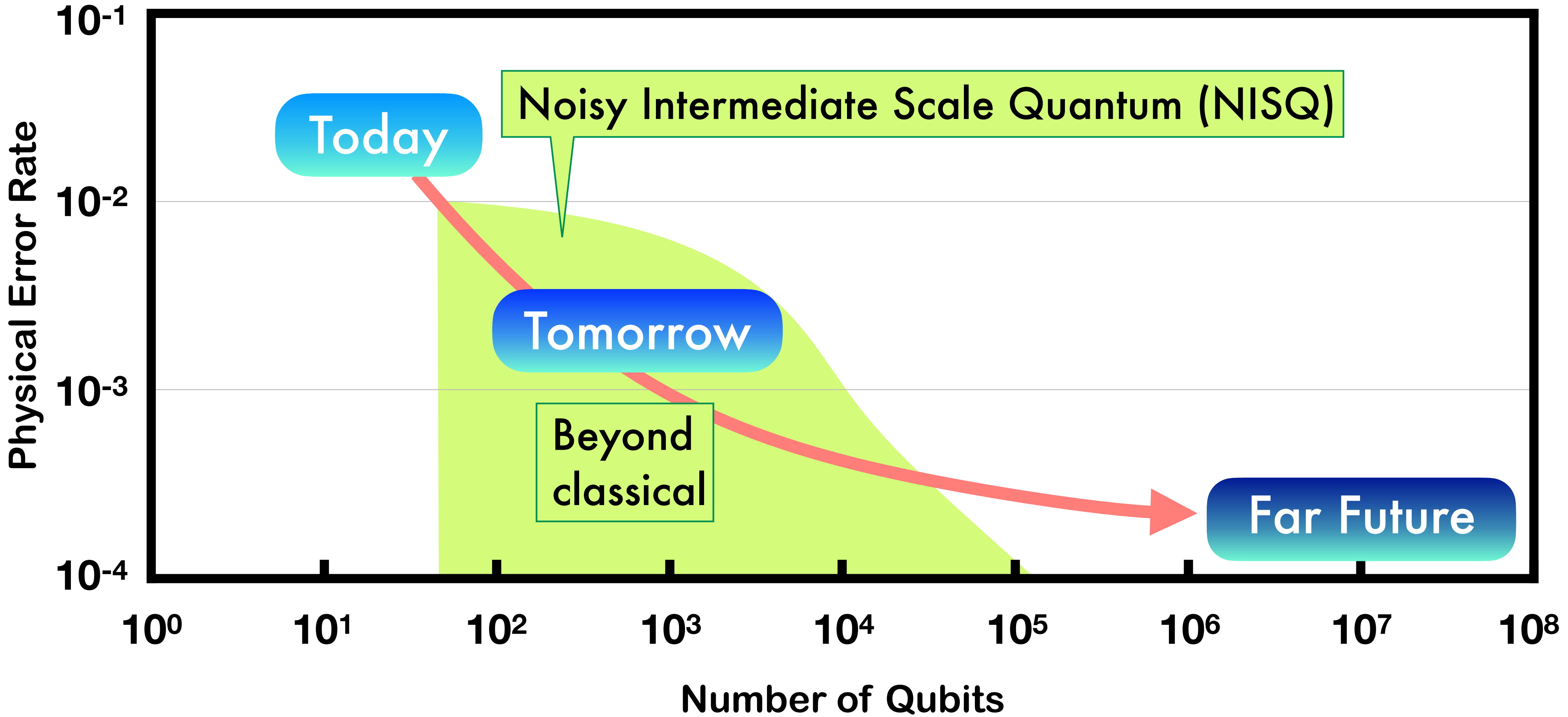
Share



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 Hardware Roadmap



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

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

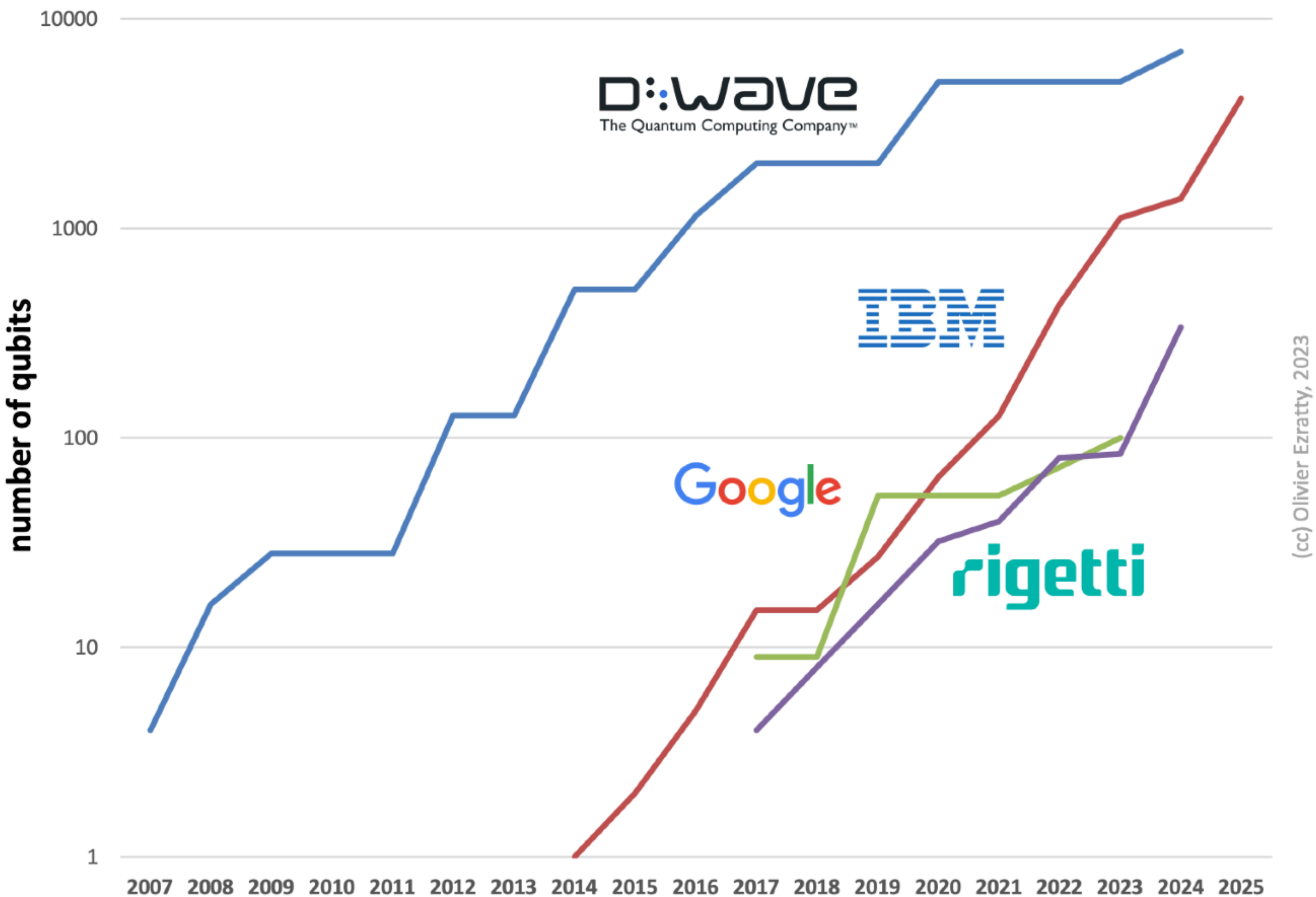


Figure 6: evolution of the number of physical qubits with D-Wave, IBM, Google and Rigetti. Compilation: Olivier Ezratty.

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

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

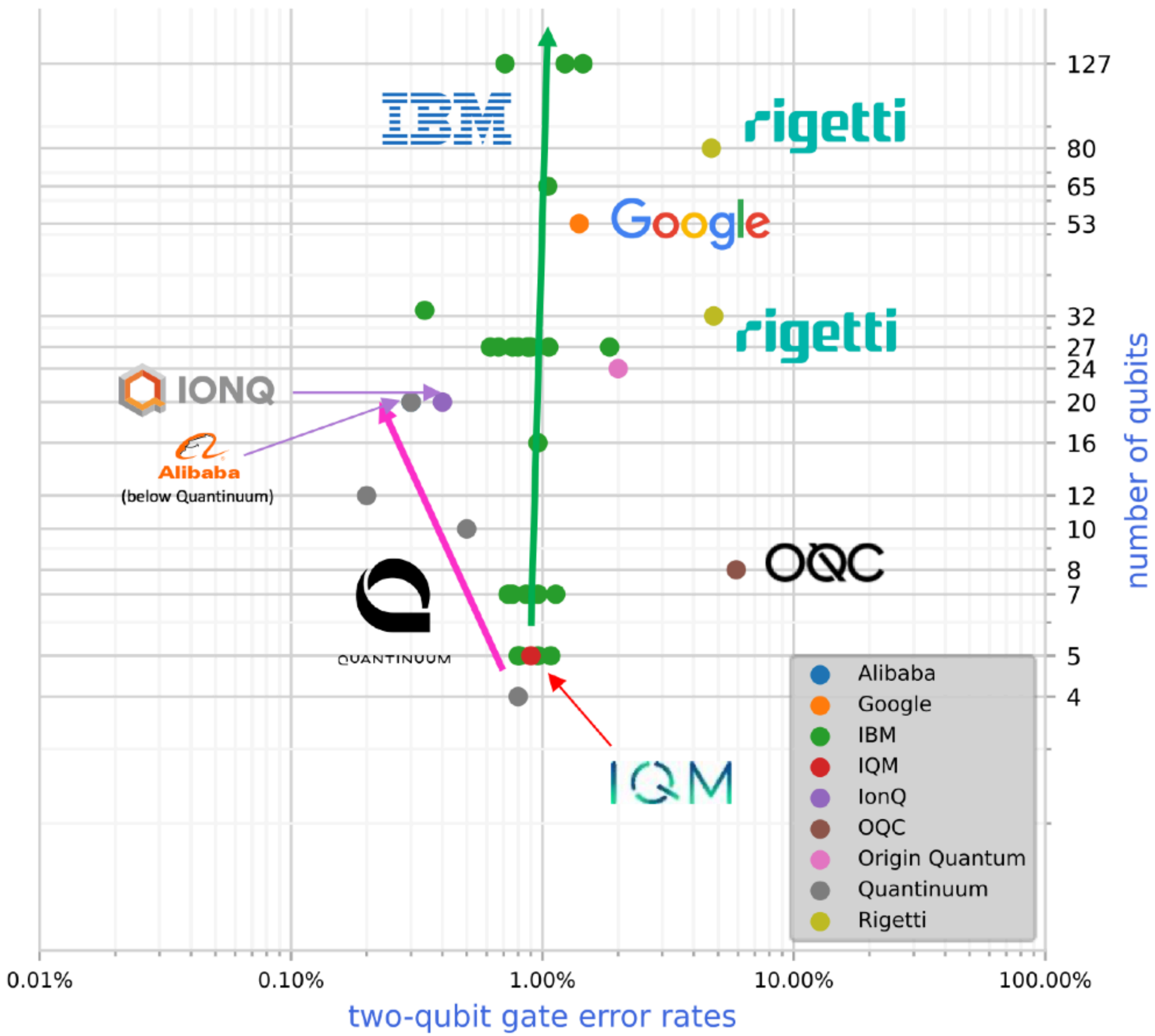


Figure 9: scatter plot of qubit numbers and two-qubit gate error rates for commercial vendors. Source: vendor fidelities numbers compiled by Olivier Ezratty as of March 2023.

Willow System Metrics

Number of qubits	105
Average connectivity	3.47 (4-way typical)

Quantum Error Correction (Chip 1)

Single-qubit gate error[1] (mean, simultaneous)	0.035% ± 0.029%
Two-qubit gate error[1] (mean, simultaneous)	0.33% ± 0.18% (CZ)
Measurement error (mean, simultaneous)	0.77% ± 0.21% (repetitive, measure qubits)
Reset options	Multi-level reset (|1) state and above) Leakage removal (|2) state only)
T_1 time (mean)	68 µs ± 13 µs[2]
Error correction cycles per second	909,000 (surface code cycle = 1.1 µs)
Application performance	$\Lambda_{3,5,7} = 2.14 \pm 0.02$

Random Circuit Sampling (Chip 2)

Single-qubit gate error[1] (mean, simultaneous)	0.036% ± 0.013%
Two-qubit gate error[1] (mean, simultaneous)	0.14% ± 0.052% (iswap-like)
Measurement error (mean, simultaneous)	0.67% ± 0.51% (terminal, all qubits)
Reset options	Multi-level reset (|1) state and above) Leakage removal (|2) state only)
T_1 time (mean)	98 µs ± 32 µs[2]
Circuit repetitions per second	63,000
Application performance	XEB fidelity depth 40 = 0.1%
Estimated time on Willow vs classical supercomputer	5 minutes vs. 10^{25} years

Breaking limitation of quantum annealer in solving optimization problems under constraints

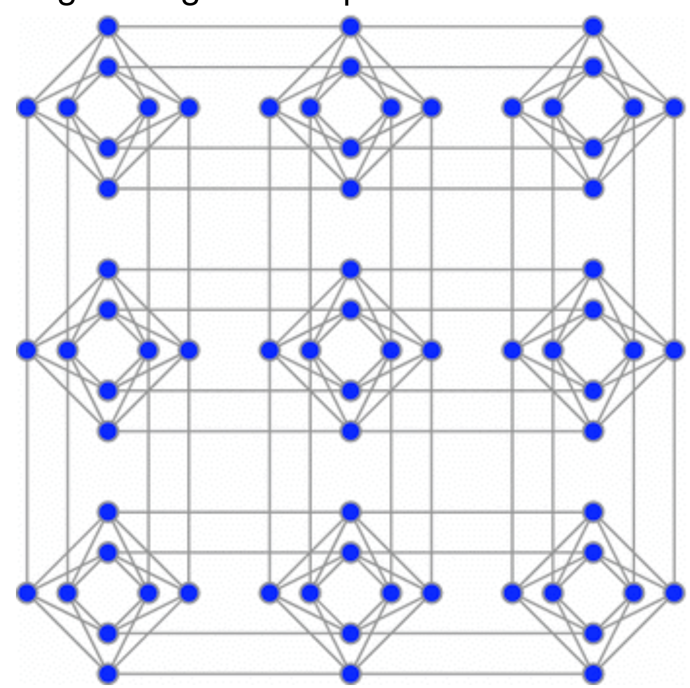
Masayuki Ohzeki[1,2,3*]

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.

<u>Supply chain logistics</u>
<u>Route Optimization</u>
<u>Portfolio management</u>
<u>Nurse scheduling problem</u>
<u>Image recognition</u>
Remote sensing imagery
Classifier optimization

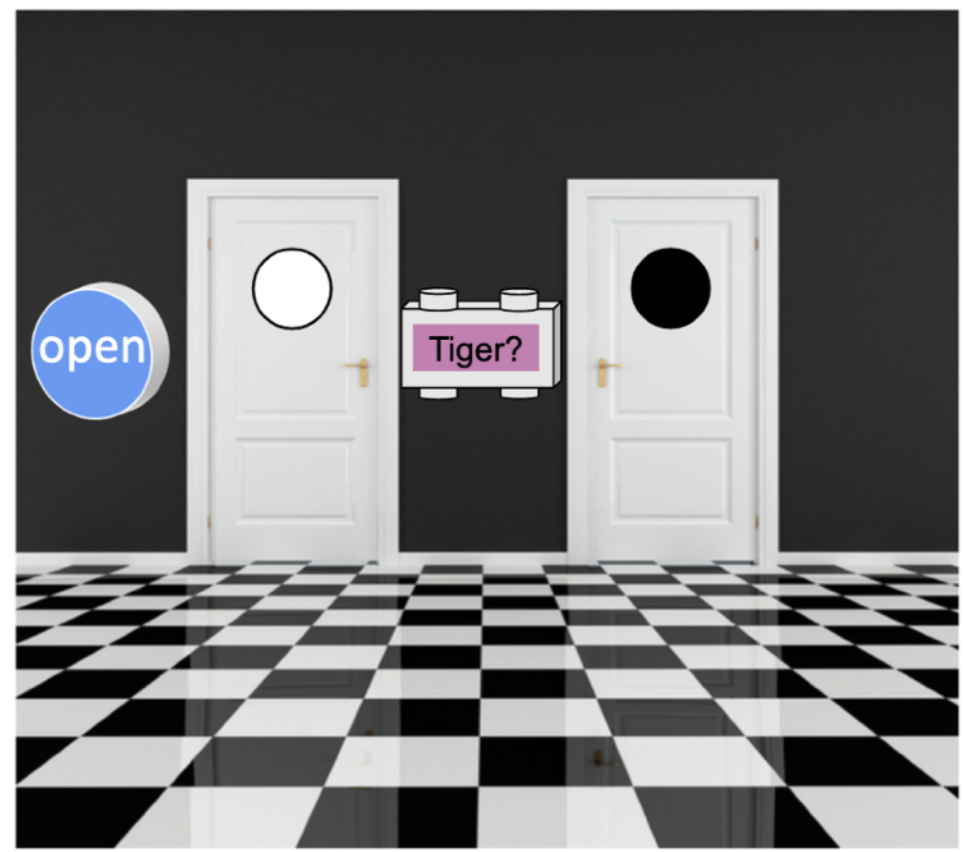
Drug discovery
Material science
Seismic inversion
Quantum simulation
Financial modeling
Cryptography
Better batteries
Cleaner fertilization
Electronic material discovery



$ vs Tiger

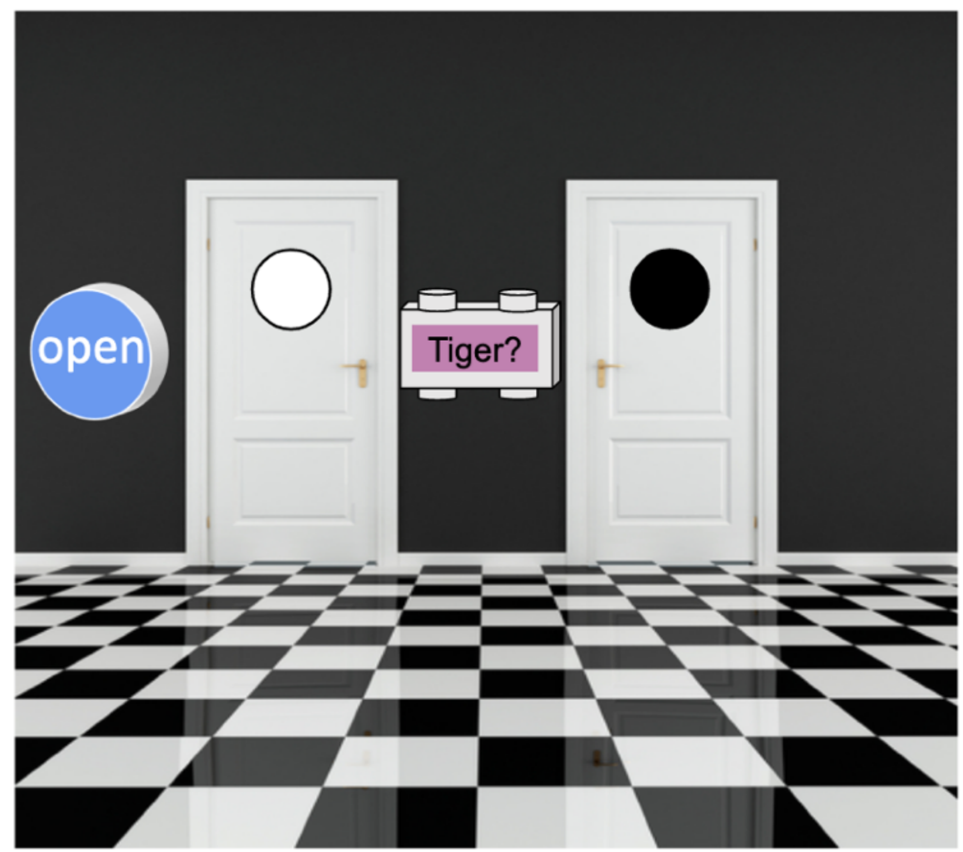
- Teaching quantum information science to high-school and early undergraduate students by Sophia Economou, Terry Rudolph, Edwin Barnes, 2005.07874
- You encounter two doors: Money behind at least one door

- Tiger might be lurking behind one door



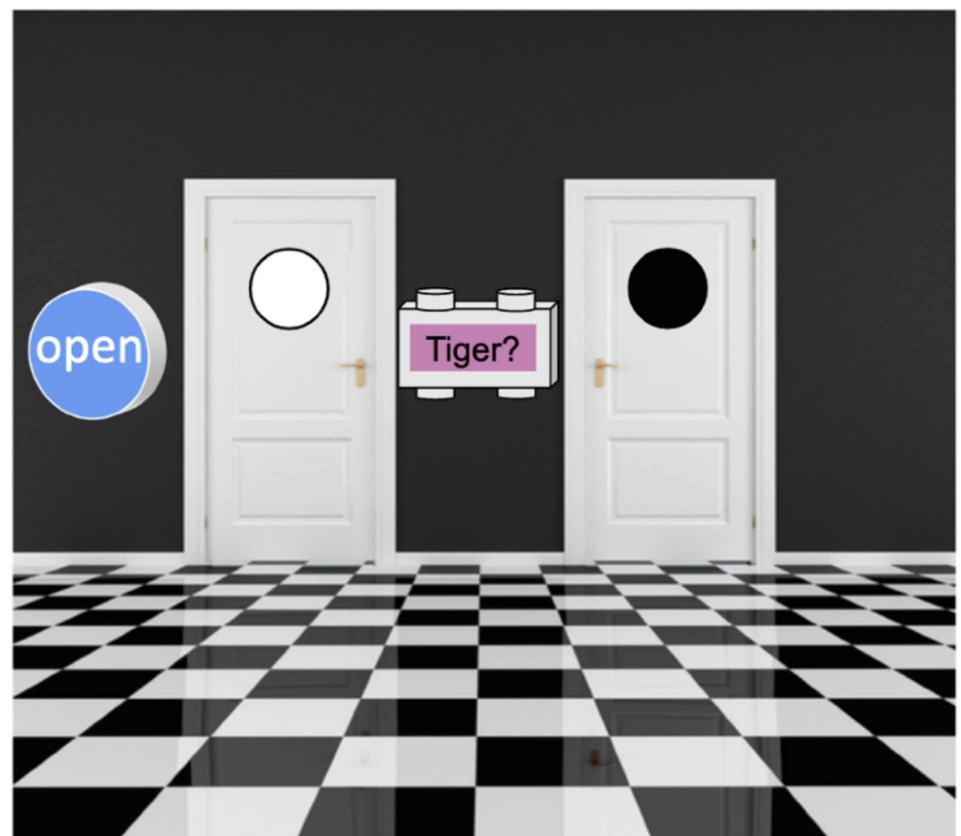
$ vs Tiger

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

$ vs Tiger

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

	In	Out	In	Out	In	Out
Door	0	0	0	0	0	0
Open?	1	1	1	1	1	0
Door	1	1	1	1	1	1
Open?	1	0	1	1	1	1

1 = no tiger
0 = tiger

$ vs Tiger

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

	In	Out
Door Open?	0 1	0 1
Door Open?	1 1	1 0

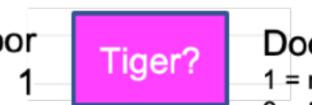
In	Out
0 1	0 1
1 1	1 1

In	Out
0 1	0 0
1 1	1 1

1 = no tiger
0 = tiger

$ vs Tiger

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



1 = no tiger
0 = tiger

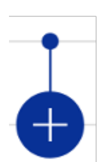
	In	Out
Door	0	0
Open?	1	1
Door	1	1
Open?	1	0

In	Out
0	0
1	1
1	1
1	1

In	Out
0	0
1	0
1	1
1	1

In	Out
0	0
1	0
1	1
1	1

Conditional NOT



Identity

Both are possible.

$ vs Tiger

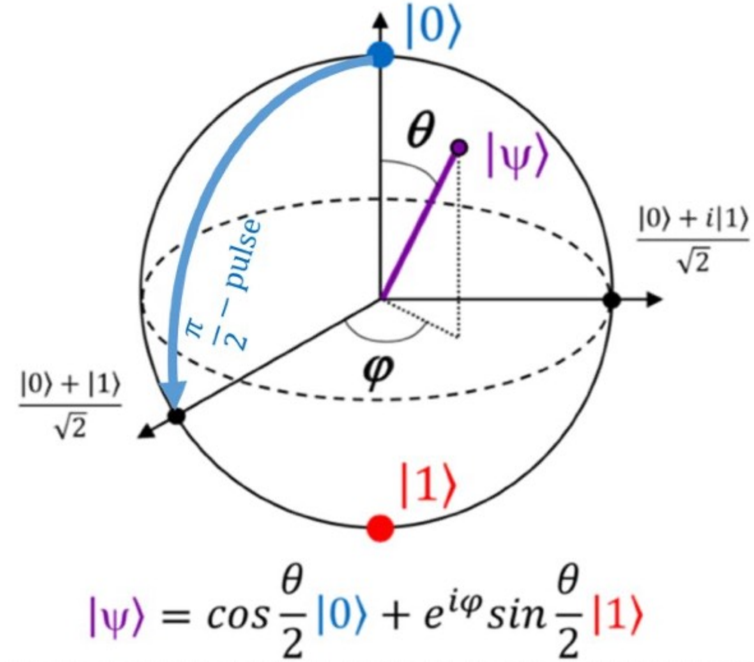
- Challenge: We can't change the tiger box, but can we add gates before and/or after it such that we can determine if there is a tiger somewhere by ONLY USING THE TIGER BOX ONCE?

- 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.

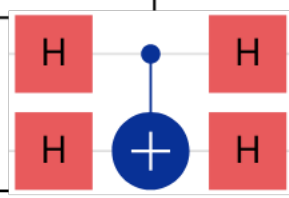


1
1

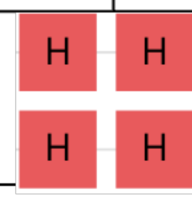
0 = tiger!, 1 = no tiger
1

$ vs Tiger

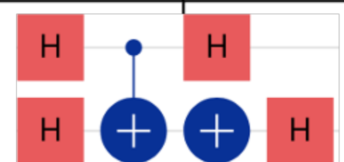
In	Out
1	0
1	1



In	Out
1	1
1	1



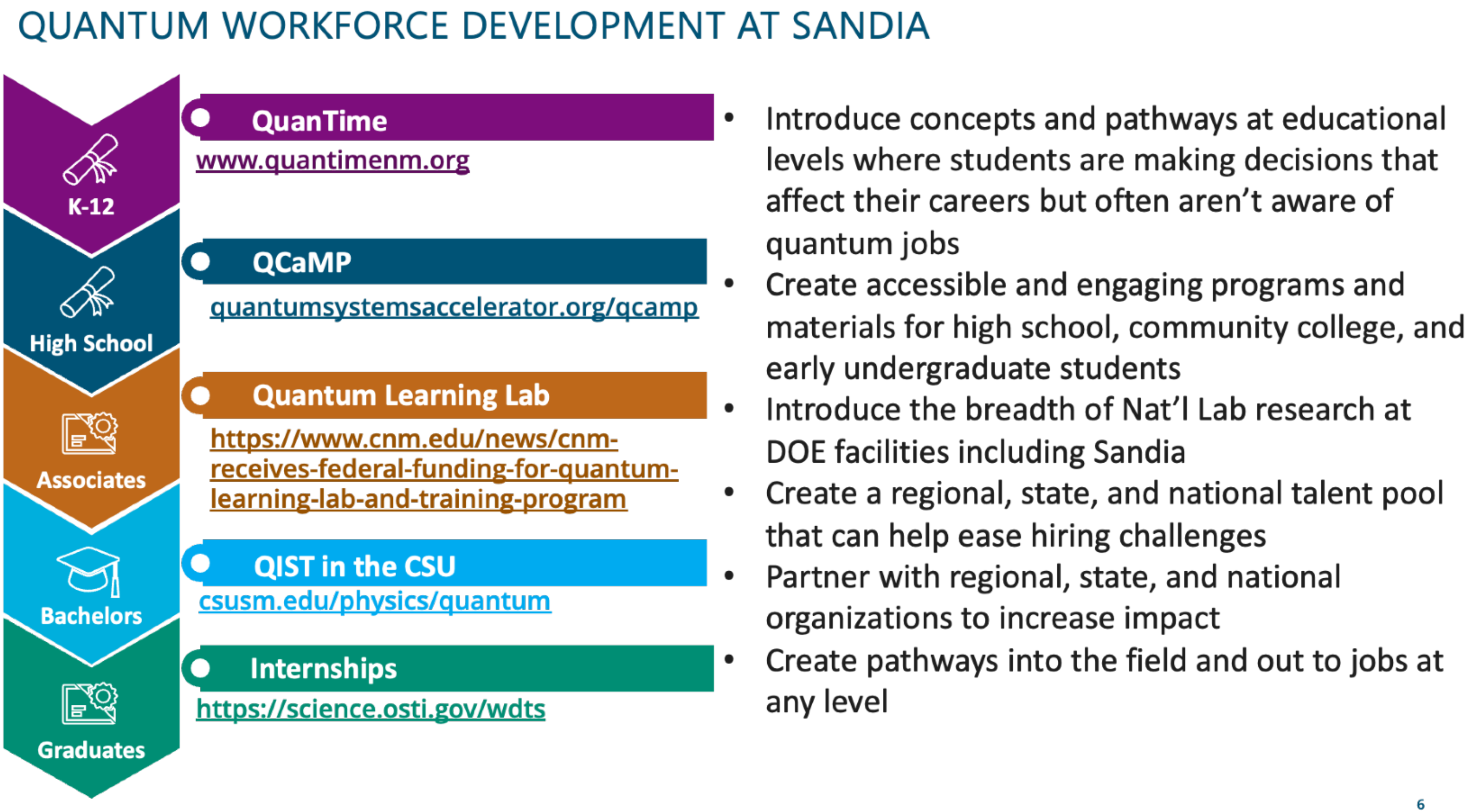
In	Out
1	0
1	1



- 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

- 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



Taken from Megan Ivory's presentation at QIST workshop 2025

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/

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.

QSA creates virtual QCaMP pilot program - 32 Students & 20 Teachers (2022)

QSA expands QCaMP to a hybrid program - 42 Students & 16 Teachers (2023)

Teacher QCaMP expands across 5 states - 83 Teachers; Student QCaMP expands to 4 weeks - 42 students (+WDTS support) (2024)

Teacher QCaMP expands across 8 states (14 cohorts) ~ 100 Teachers; (+WDTS support) Student QCaMP - 42 students (+WDTS support) (2025)

2024: 360+ Participants (cumulative)

2025: 500+ Participants (cumulative)

Sandia & LBNL participate in ORISE's JSTI program - 10 Students (2021)

QCaMP @ CNM Bridge Program- 22 Community College Students (2023)

QCaMP 1-Day Workshop at St. Vincent College - 28 K-12 Teachers (2024)

QCaMP @ CNM Bridge Program- 15 Community College Students (2024)

NM ECEP 2-Hour Workshop – 31 Educators (2024)

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.

Quantum Research

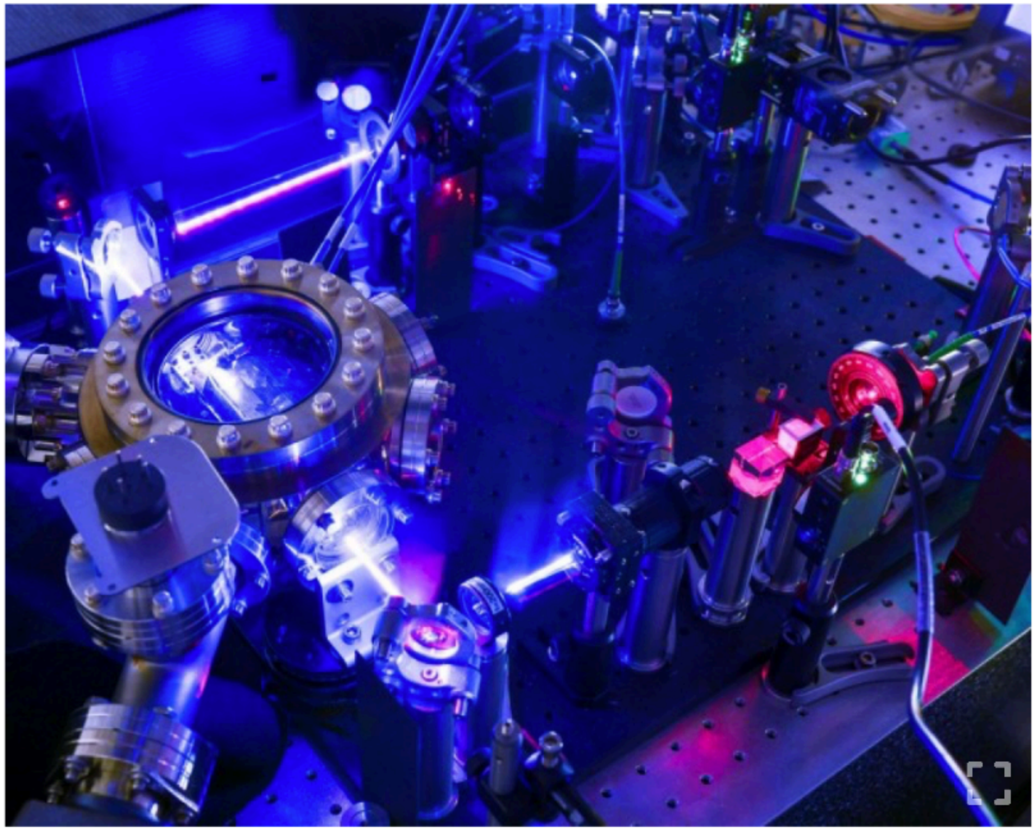
Email: nrlpao@nrl.navy.mil

History

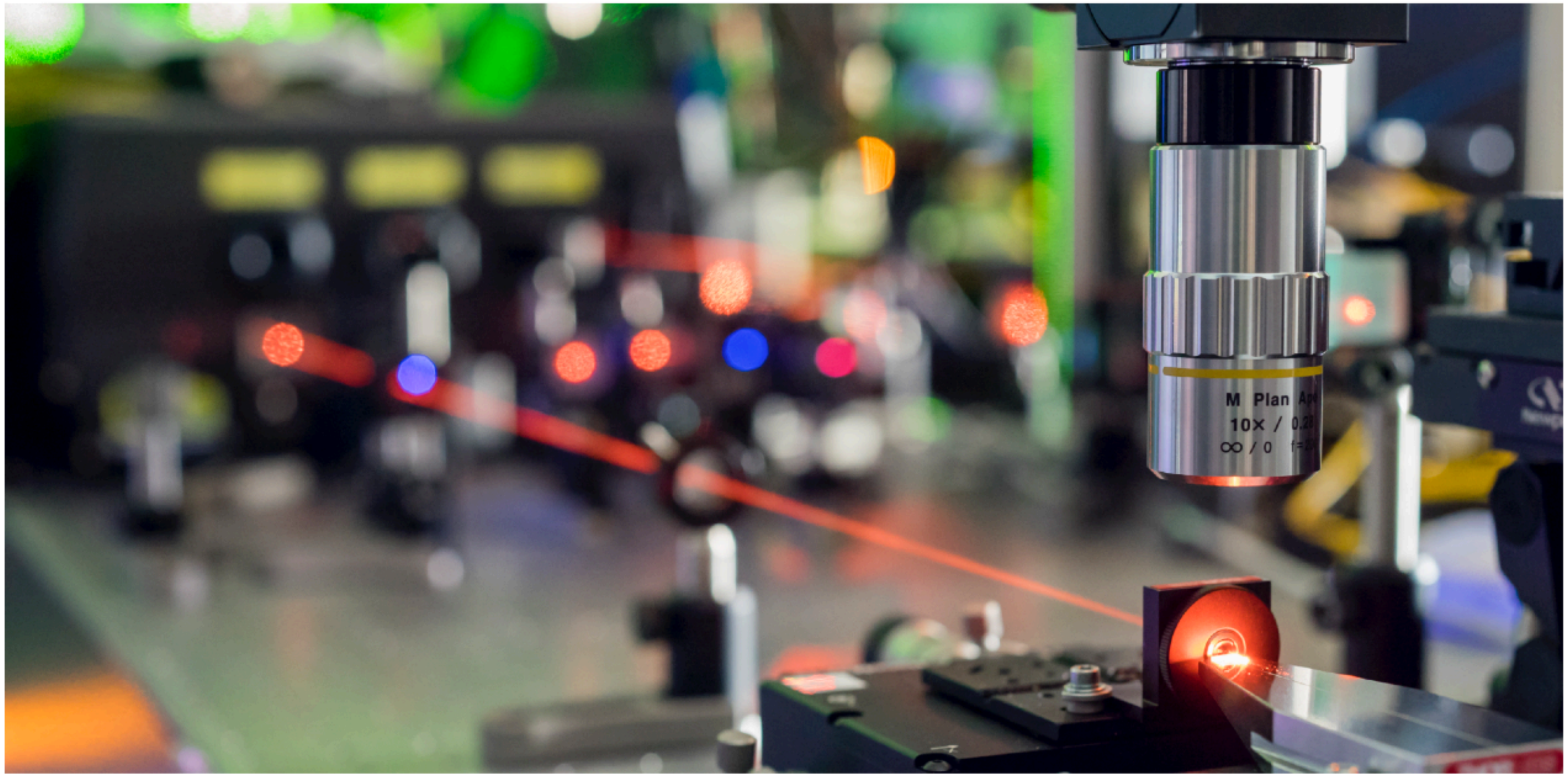
The beginning of research into Quantum Information Science (QIS) can be traced to theoretical physicist, Richard Feynman, Ph.D. In 1982 he proposed that computers that take advantage of quantum mechanical principles may have certain advantages over classical computers. Since then, researchers have proposed 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



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

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).

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

Not sure whether there will a school in 2025

Undergraduate Quantum Summer School

Aug 14 and 15, 2024 Northwestern University

https://forms.gle/BaNkcoRL3ozeQPit8

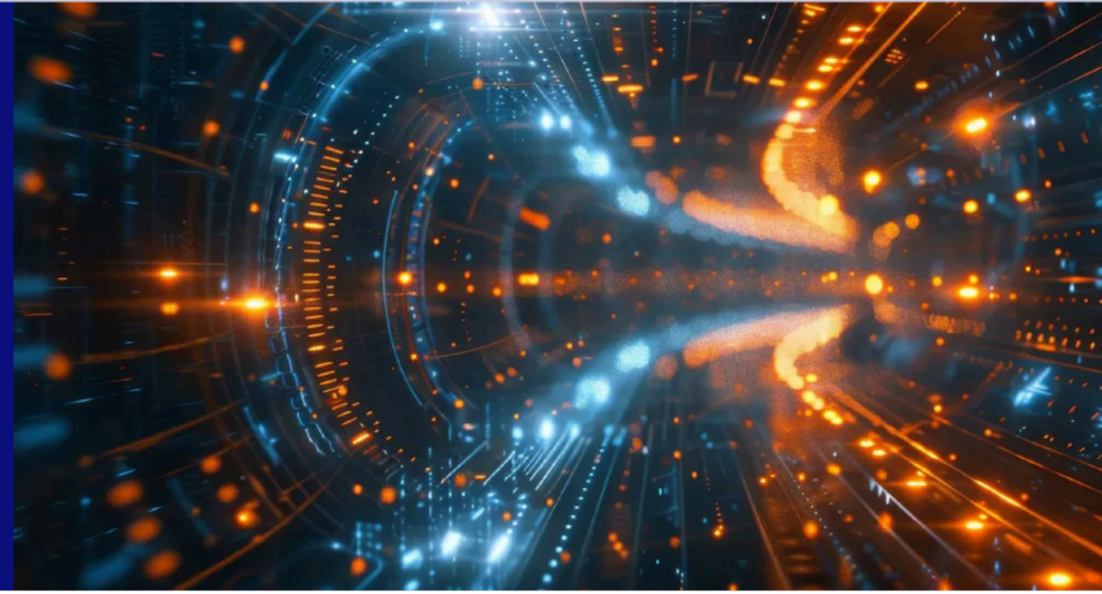
What to expect:

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.

LANL

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

managed by Brookhaven Science Associates
for the U.S. Department of Energy

QIS 100: Applied Quantum Computing Virtual Program, June 2025

Application Period Opens February 2025

C^{2}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.

PREREQUISETES: 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.

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

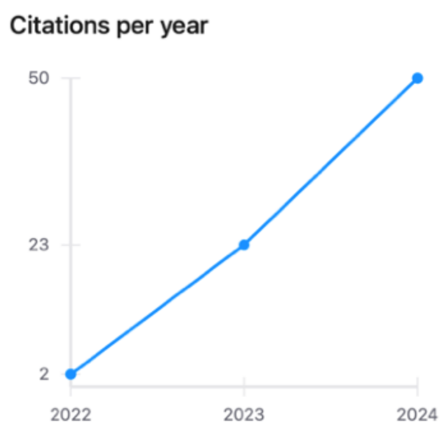
Google Summer of Code program is intended for advanced students who are already familiar with AI or quantum computing.

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

Enrico Fontana,[1,2] Dylan Herman,[1,*] Shouvanik Chakrabarti,[1] Niraj Kumar,[1] Romina Yalovetzky,[1] Jamie Heredge,[1,3] Shree Hari Sureshbabu,[1] and Marco Pistoia[1]

[1] *Global Technology Applied Research, JPMorgan Chase*
[2] *Computer and Information Sciences, University of Strathclyde*
[3] *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

1Password | Remote | $190,000 - $258,000 a year

You must create an Indeed account before continuing to the company website to apply

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:

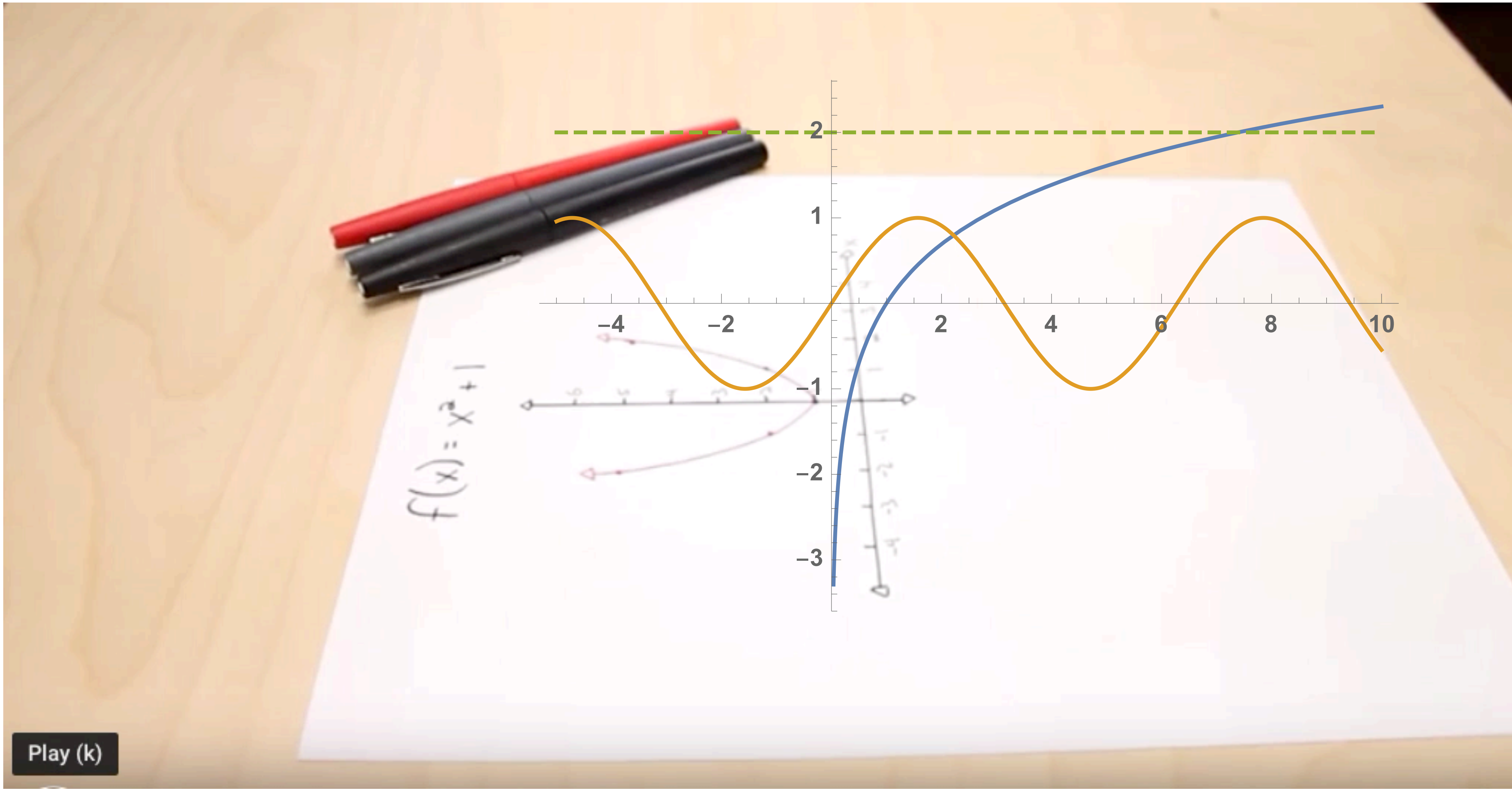
- Experience with post-quantum cryptography (e.g., lattice-based algorithms) in theory or practice
- Familiarity with evolving cryptographic standards and bodies (e.g., NIST), and how they shape implementation decisions

- You drive delivery and long-term planning, shaping roadmaps that balance

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.

Q: solve for “x”



$$y = x^2 + 1$$

from Welch Labs

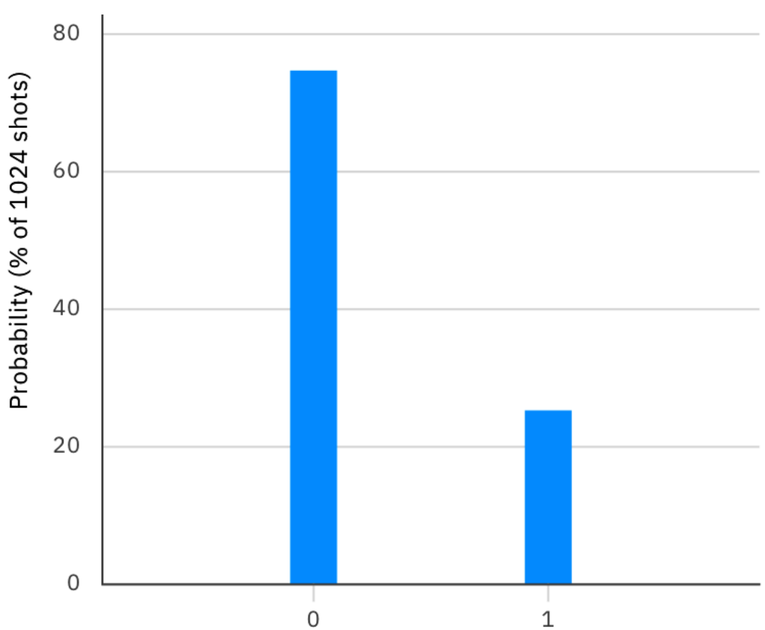
Inner product

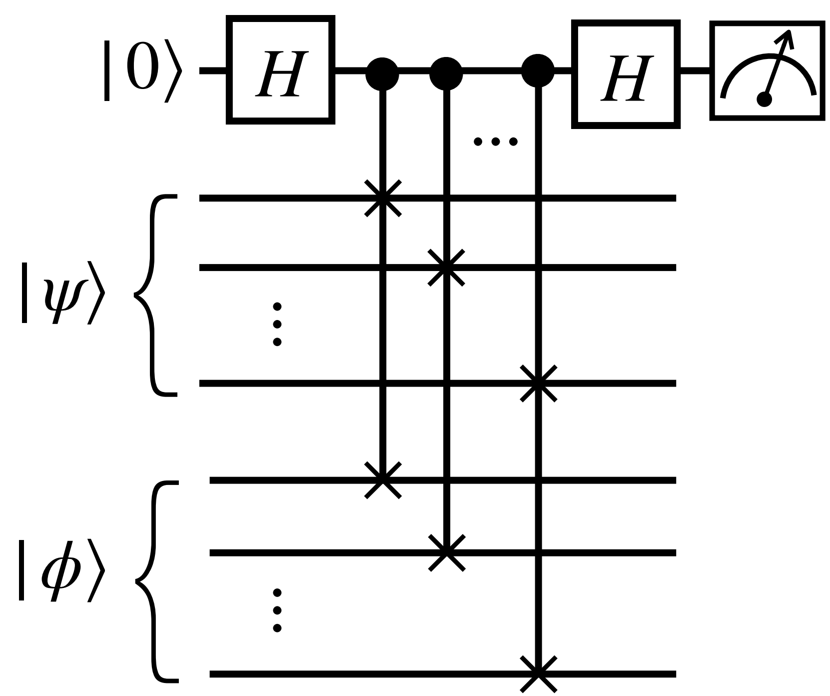
- Let $|\psi\rangle, |\phi\rangle \in \mathbb{C}^{2^n}$ be two $N = 2^n$ dimensional vectors. How to compute the magnitude of the inner product $|\langle\phi|\psi\rangle|^2$?
- Classical
  - $N = 2^n$ multiplications and additions
  - Decompose multiplications and additions as NAND gates
- Quantum
  - Run the following circuits with $2n + 1$ qubits and $n + 2$ gates
  - $\mathrm{Prob}(0) - \mathrm{Prob}(1) = |\langle\phi|\psi\rangle|^2$

$$|\psi\rangle = (\psi_1, \cdots, \psi_N)$$

$$|\phi\rangle = (\phi_1, \cdots, \phi_N)$$

$$\langle\phi|\psi\rangle = \sum_{i=1}^{N} \phi_i^* \psi_i$$

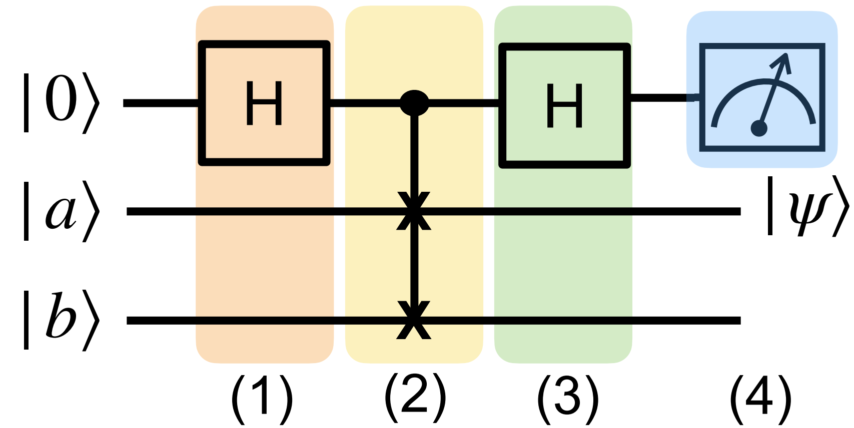




Proof: Inner product

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

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



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

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

(3) $$|\psi\rangle = H\,SWAP\,H\left(|0\rangle|a\rangle|b\rangle\right) = \frac{1}{\sqrt{2}}\,H(|0\rangle|a\rangle|b\rangle + |1\rangle|b\rangle|a\rangle)$$

$$= \frac{1}{2}|0\rangle\left(|a\rangle|b\rangle + |b\rangle|a\rangle\right) + \frac{1}{2}|1\rangle\left(|a\rangle|b\rangle - |b\rangle|a\rangle\right)$$

sum of the “unswapped” and the “swapped”

difference

(4) $$P(0) = |(\langle 0 \otimes I)|\psi\rangle|^2 = \frac{1}{2} - \frac{1}{2}|\langle a|b\rangle|^2$$

$$P(1) = |(\langle 0 \otimes I)|\psi\rangle|^2 = \frac{1}{2} + \frac{1}{2}|\langle a|b\rangle|^2$$

$\Rightarrow$

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

Experimental realization

PRL **110,** 230501 (2013) PHYSICAL REVIEW LETTERS week ending 7 JUNE 2013

Experimental Quantum Computing to Solve Systems of Linear Equations

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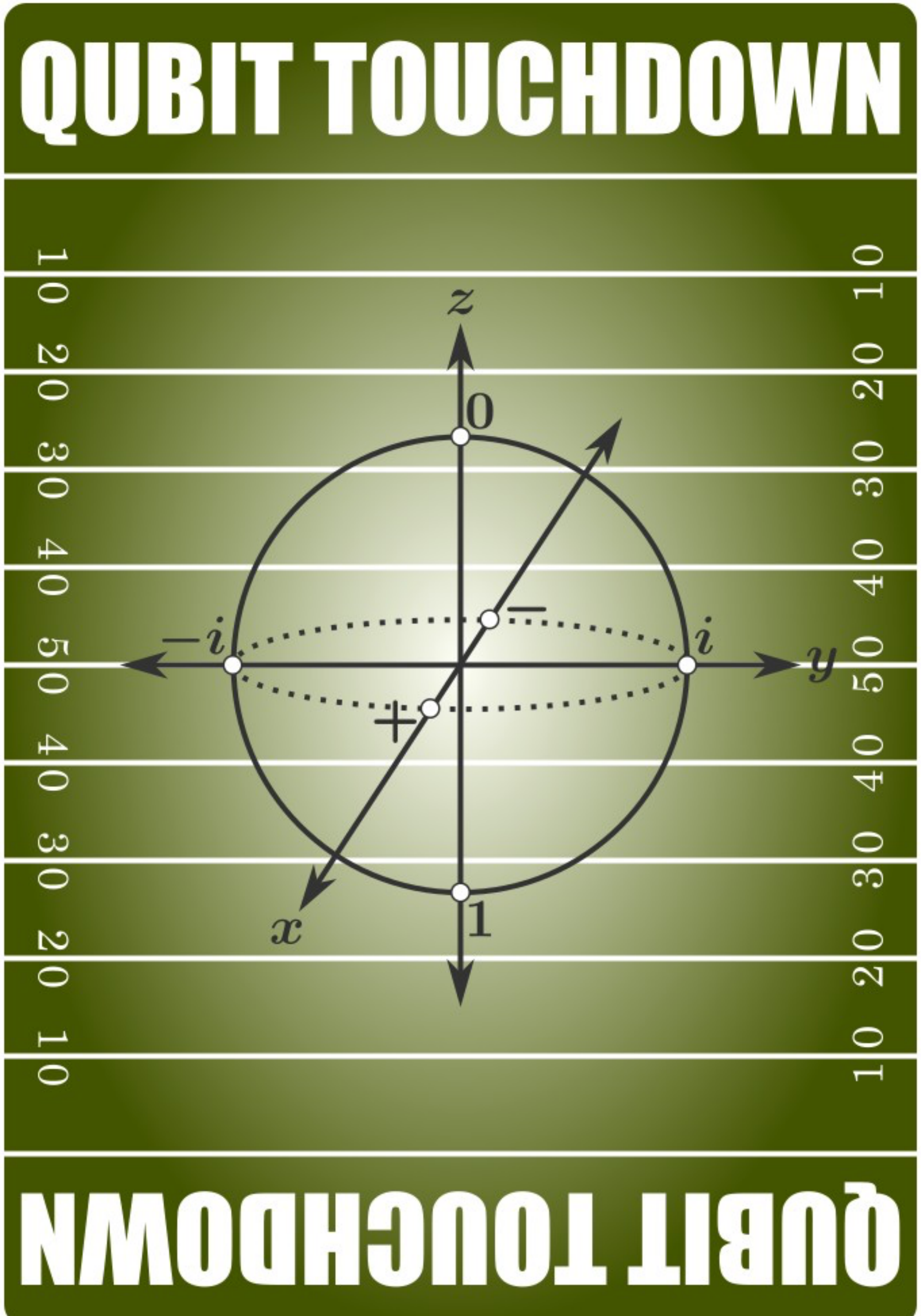
Solving linear systems of equations is ubiquitous in all areas of science and engineering. With rapidly growing data sets, such a task can be intractable for classical computers, as the best known classical algorithms require a time proportional to the number of variables N. A recently proposed quantum 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 2×2 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.

USC Study Demonstrates Unconditional Exponential Quantum Scaling Advantage

- Demonstration of Algorithmic Quantum Speedup for an Abelian Hidden Subgroup Problem



$$X: \qquad 0 \longleftrightarrow 1$$

$$i \longleftrightarrow -i$$

$$\sqrt{X}: \qquad \begin{tikzcd} & 0 \arrow[dr, bend left] & \\ i \arrow[ur, bend left] & & -i \arrow[dl, bend left] \\ & 1 \arrow[ul, bend left] & \end{tikzcd}$$

$$H: \qquad 0 \longleftrightarrow +$$

$$1 \longleftrightarrow -$$