Introduction to Quantum Computing

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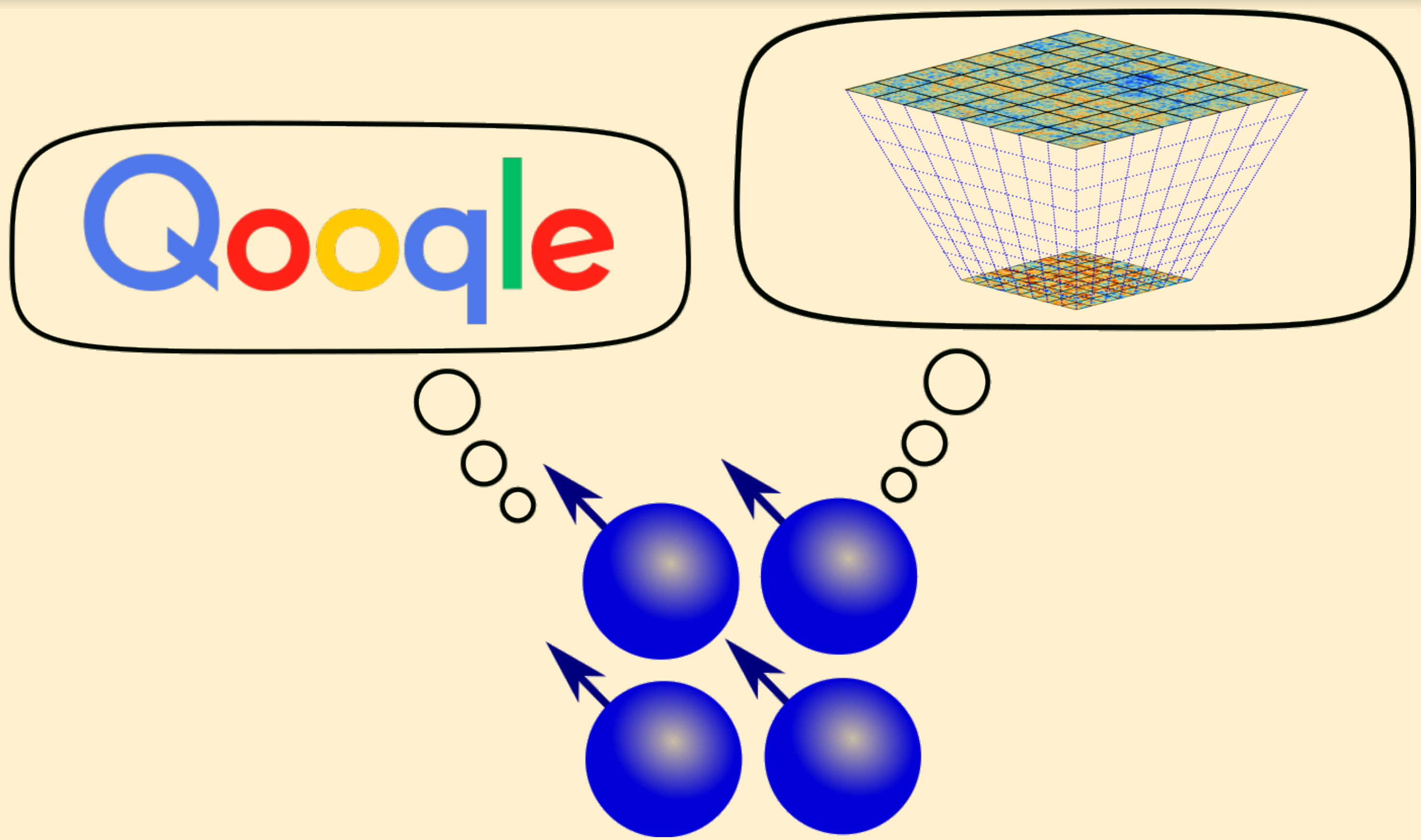
Particle Physics Division (Theory)

July 2, 2020



Lots of $$, Lots of Interest, Lots of Hype

So, today I hope to answer one question

...which is really a bunch of smaller questions

- What is wrong with classical computing?
- How do quantum computers work?
- What can I do today?
- What does the future look like?

Who am I?

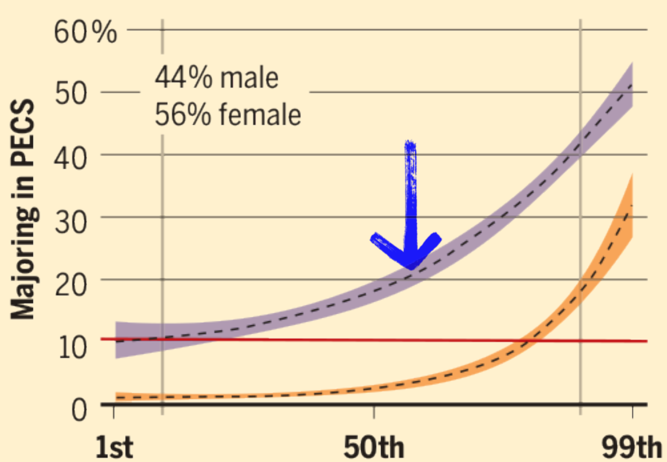
Who majors in PECS?

The shaded areas represent one standard error above and below the estimated means.

Males Females

All students

Males scoring at or below the 1st percentile of all students' science, technology, engineering, and math (STEM) achievement major in physics, engineering, and computer science (PECS) at the same rate (10%, horizontal red line) as females scoring at the 80th percentile. The gap is significant at all levels of achievement. The male:female ratio in PECS is much larger in the 1st decile (10:1) than in the 10th decile (2:1) (vertical gray lines).



Undergrad at Kansas State University

Grad School at Arizona State University

Postdoc at University of Maryland

Now, Postdoc at Fermilab

Physics GRE Score	Percentile
980	93
960	91
940	89
920	87
900	84
880	82
860	79
840	76
820	72
800	69
780	65
760	62
740	58
720	54
700	50
680	46
660	42
640	37
620	33

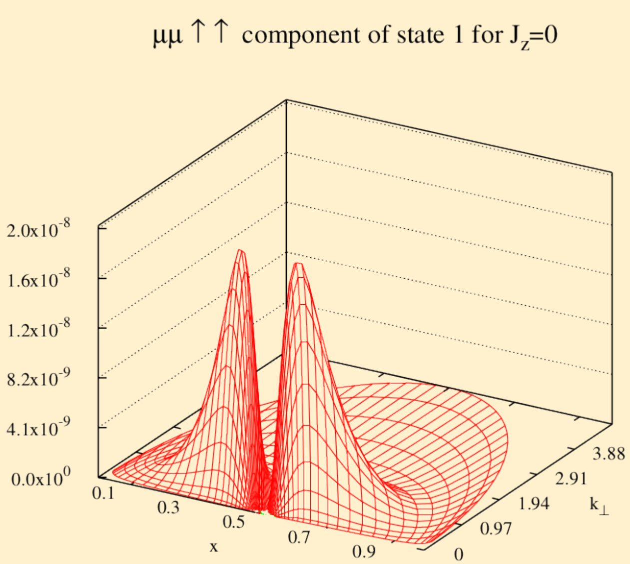
What do I do?

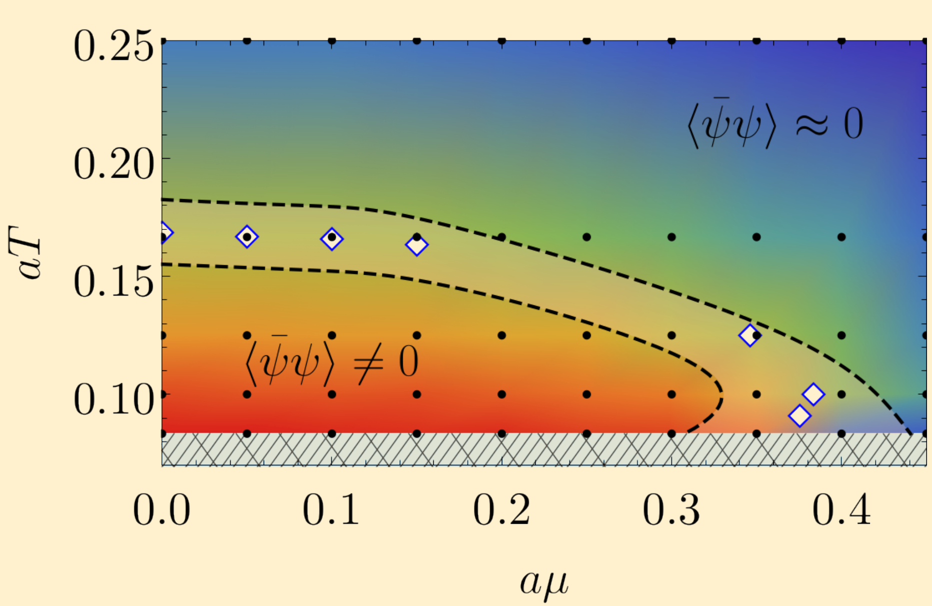
Apply computational and theoretical methods to solve problems in nonperturbative quantum field theory

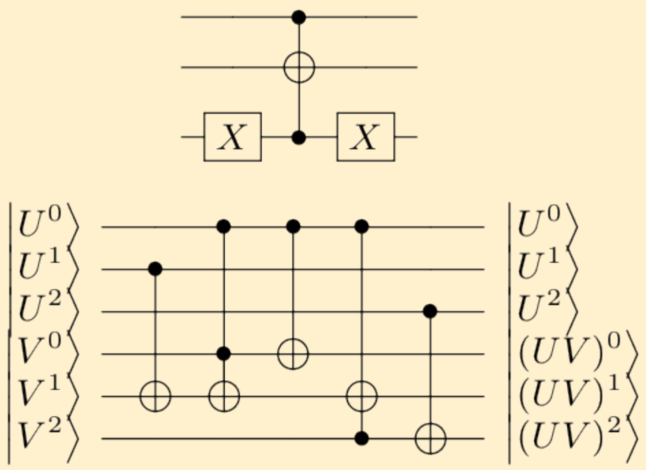
What are the decay rates of heavy-quark mesons?
How do the dynamics of QCD change in hot or dense matter?
When in the early universe do quantum effects dominate?

Sit at computer and write lots of code

Stand at blackboard and have long discussions with colleagues







What makes a classical computer?

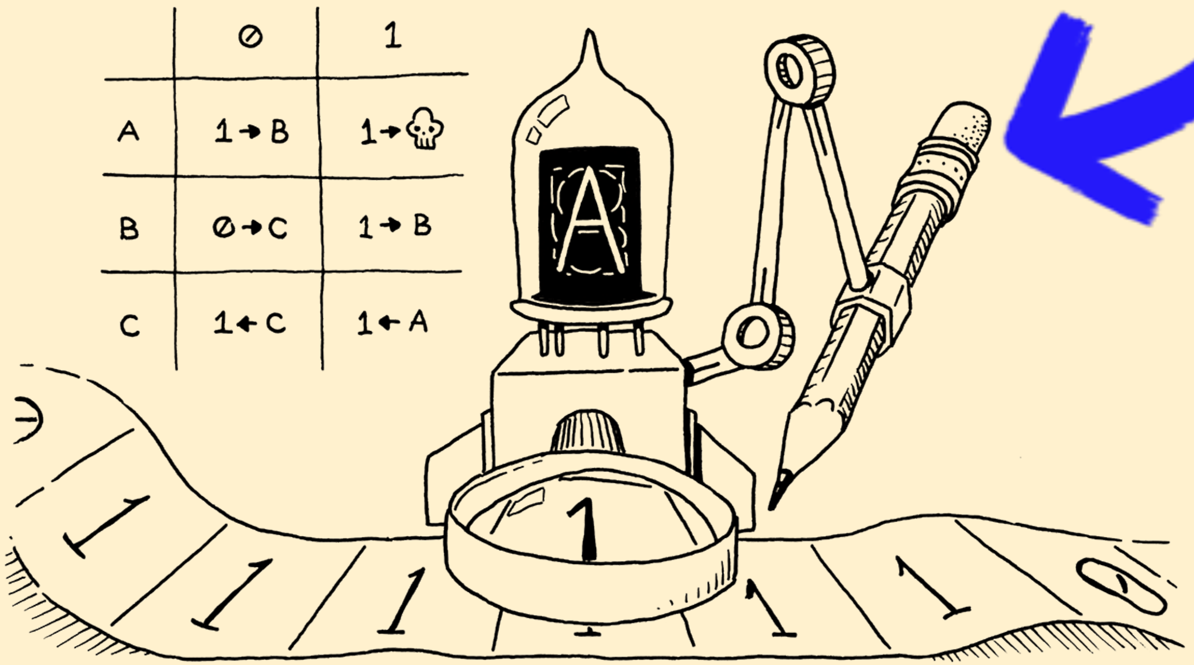

```
$mail->setFrom('from@example.com', 'Mailer');
$mail->addAddress('joe@example.net', 'Joe User');     // Add a recipient
$mail->addAddress('ellen@example.com');               // Name is optional
$mail->addReplyTo('info@example.com', 'Information');
$mail->addCC('cc@example.com');
$mail->addBCC('bcc@example.com');

$mail->addAttachment('/var/tmp/file.tar.gz');         // Add attachments
$mail->addAttachment('/tmp/image.jpg', 'new.jpg');    // Optional name
$mail->isHTML(true);                                  // Set email format to HTML

$mail->Subject = 'Here is the subject';
$mail->Body    = 'This is the HTML message body <b>in bold!</b>';
$mail->AltBody = 'This is the body in plain text for non-HTML mail clients';

if(!$mail->send()) {
 echo 'Message could not be sent.';
 echo 'Mailer Error: ' . $mail->ErrorInfo;
} else {
 echo 'Message has been sent';
}
?>
```

Universal Turing Machine

“Infinite” tape specifying states
    -Usually in binary i.e. {0,1}

“CPU” performs operations

Finite set of operations can be used to build ***<u>any</u>*** classical computation



What does a classical computer do?

- ***algorithm (n):*** a set of rules to be followed in calculations
- Problem: Sort a list of numbers
- Algorithmic Solutions:
  - Random: Rearrange at random all numbers
  - Bubble sort: Compare switch pairwise
  - QuickSort: Sort elements about pivot

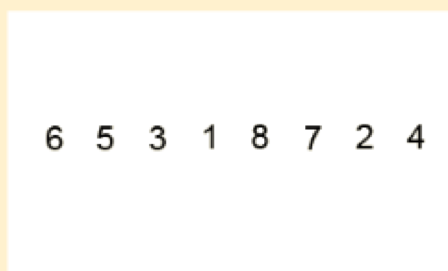
$$\begin{pmatrix} 13 & 63 & 14 \\ 68 & 52 & 30 \\ 59 & 56 & 73 \\ 4 & 54 & 32 \\ 17 & 6 & 23 \\ 47 & 96 & 38 \\ 50 & 59 & 72 \\ 39 & 64 & 44 \\ 71 & 39 & 51 \\ 85 & 6 & 11 \\ 20 & 49 & 84 \\ 46 & 62 & 68 \\ 61 & 17 & 4 \\ 41 & 77 & 83 \\ 64 & 21 & 7 \end{pmatrix}$$

How about a visual demonstration?

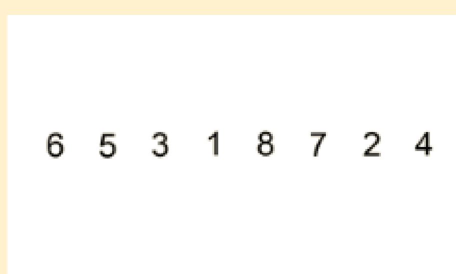
How do algorithms differ? Complexity!

- **Time complexity:** How long will it take?
- **Space complexity:** How much memory does it take?
- ***Big O notation:*** Asymptotic behavior as a function of the size of the array, n

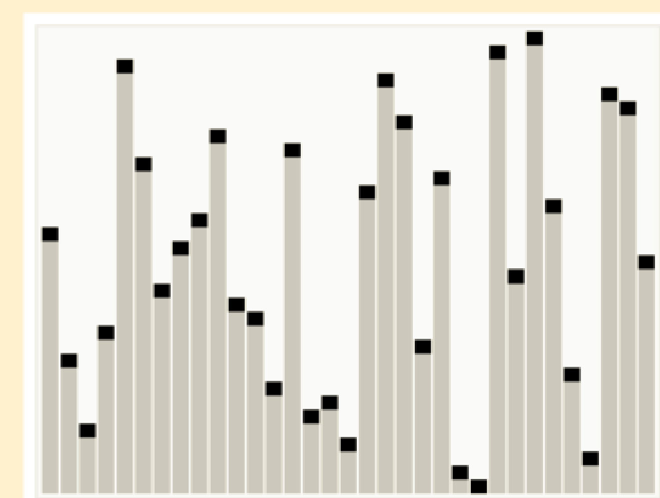
- **Bubble** $O(n^2)$



- **Insertion** $O(n^2)$

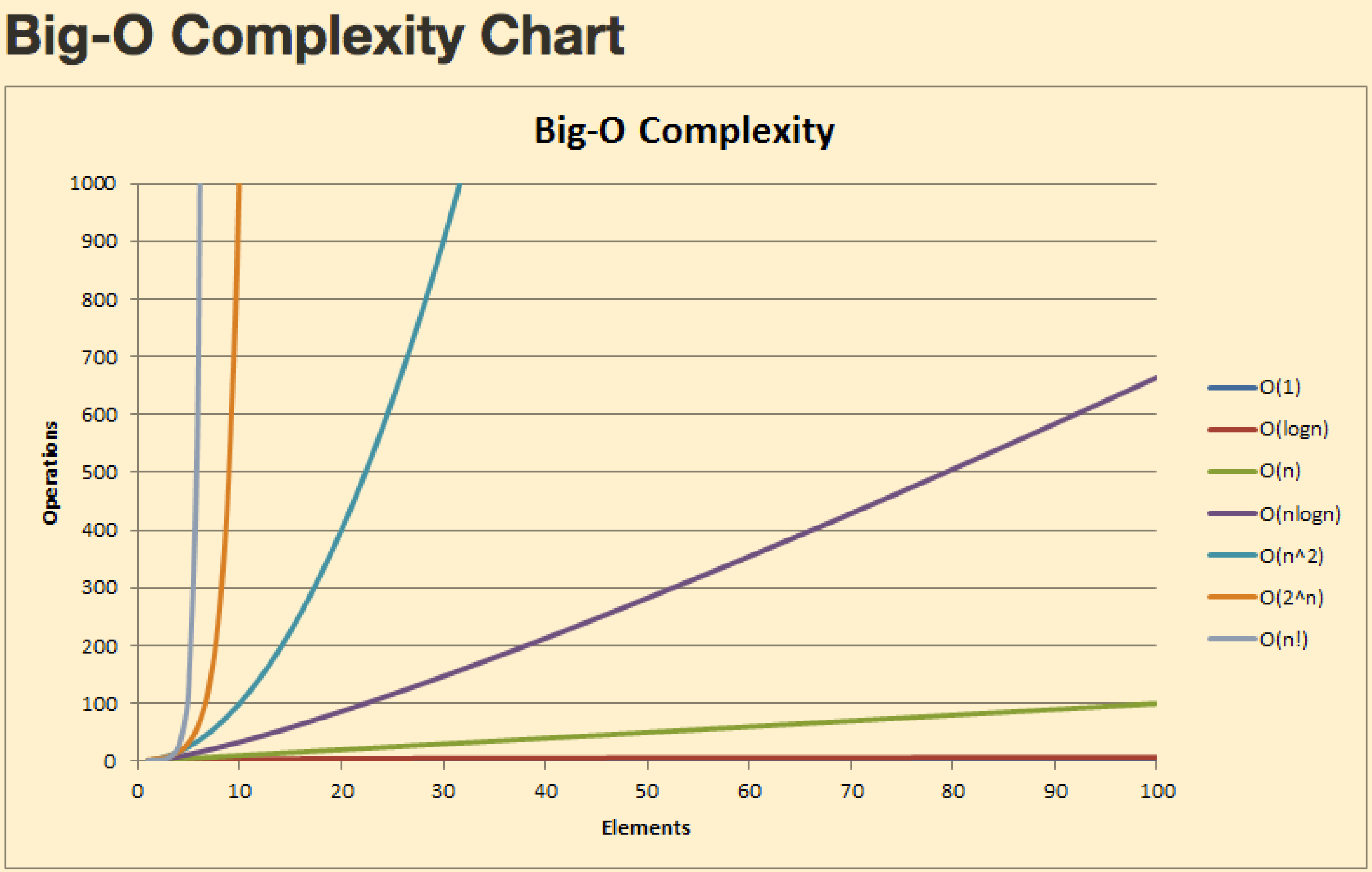


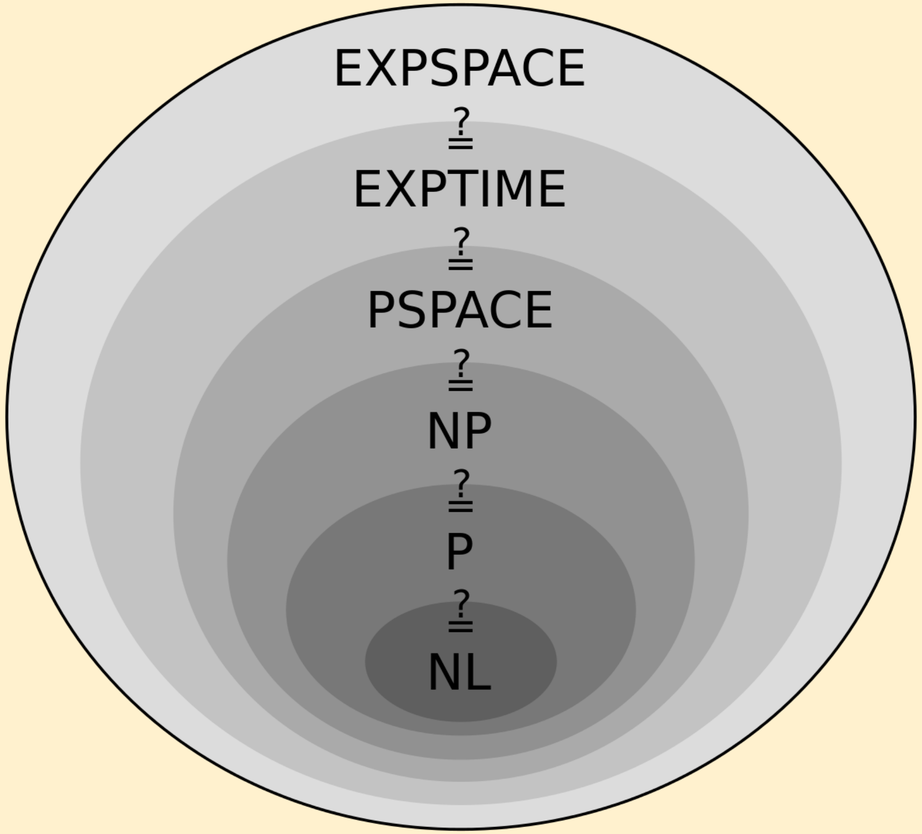
- **QuickSort** $O(n \log n)$



What's wrong with classical computing?

- Problems can be classified by their complexity

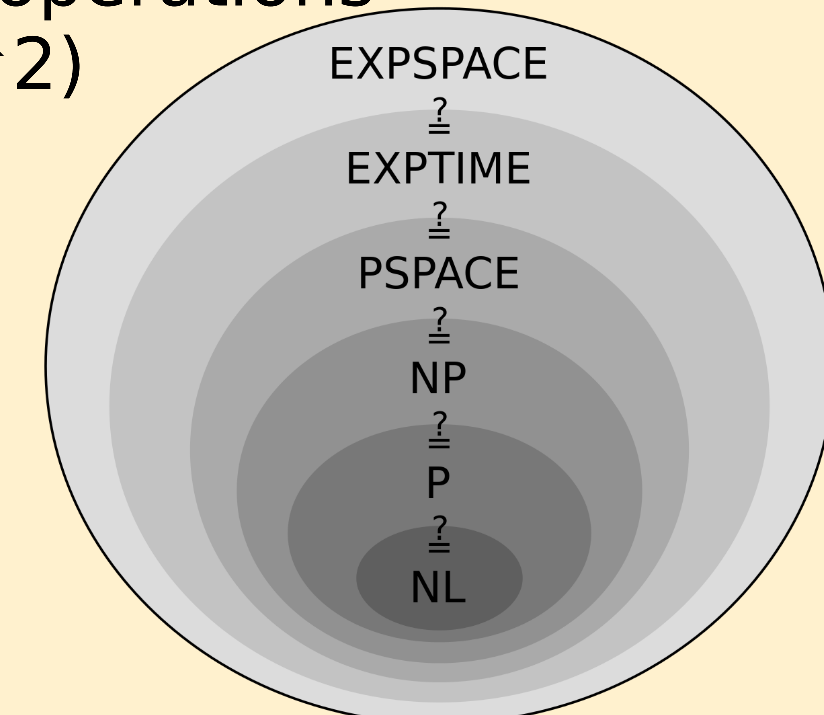




https://github.com/gibsjose/cpp-cheat-sheet

P vs. NP

- **P problems:** solvable by using a number of operations that scale with the size like a power i.e. O(n^2)



- **NP problems:** solvable by using a number of operations that scales faster i.e. O(2^n)

- Supercomputing resources are required to solving NP problems for smallish n

- Is *N=NP?* Answer is worth a million dollars (and fame)

How the internet depends on complexity

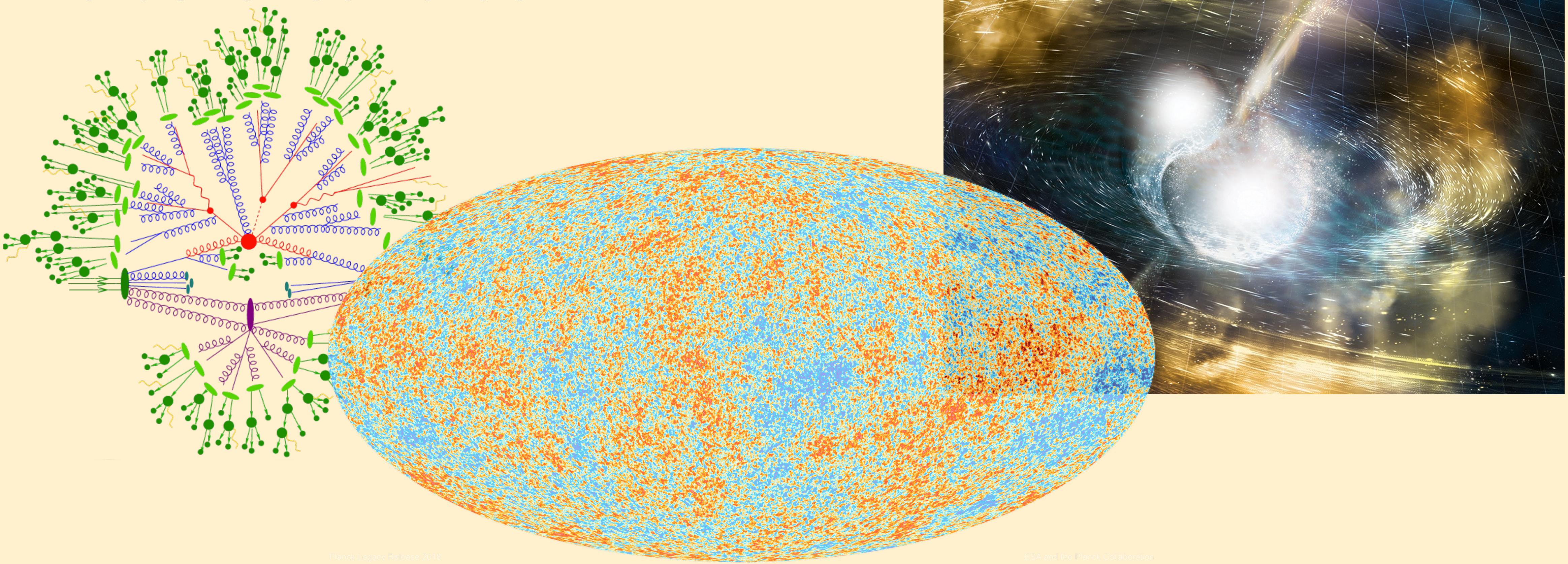
- RSA encryption is used to communicate online
- Based on Prime Factorization, *hoped* to be in NP
- Best known algorithm:

$$\exp\left(\left(\sqrt[3]{\frac{64}{9}}+o(1)\right)(\ln n)^{\frac{1}{3}}(\ln\ln n)^{\frac{2}{3}}\right)$$

- If we woke up to algo in P→ Chaos

Why physics struggles with NP...

- The quantum nature of physics literally causes certain problems to have high computational complexity
- Nearly **<u>any</u>** hard problem in real time or finite density is believed to be NP.



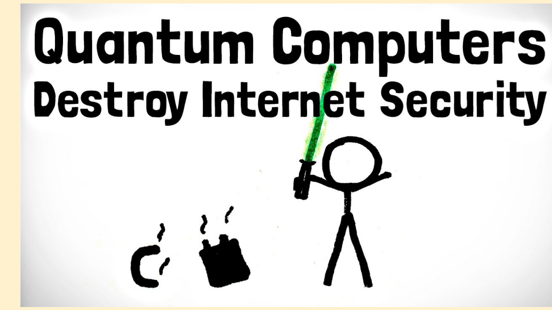
...This is how nature works

- Classical computers are great as simulate classical processes

- But nature is fundamentally quantum, so I need a quantum computer to efficiently simulate it

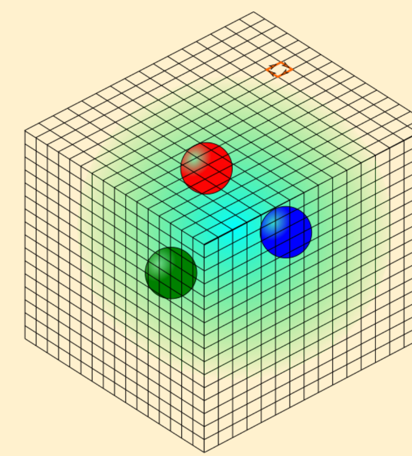
What could a quantum computer do someday?

- **Shor's Algorithm** efficiently factorize
  - This is why people freak out!



Minute Physics

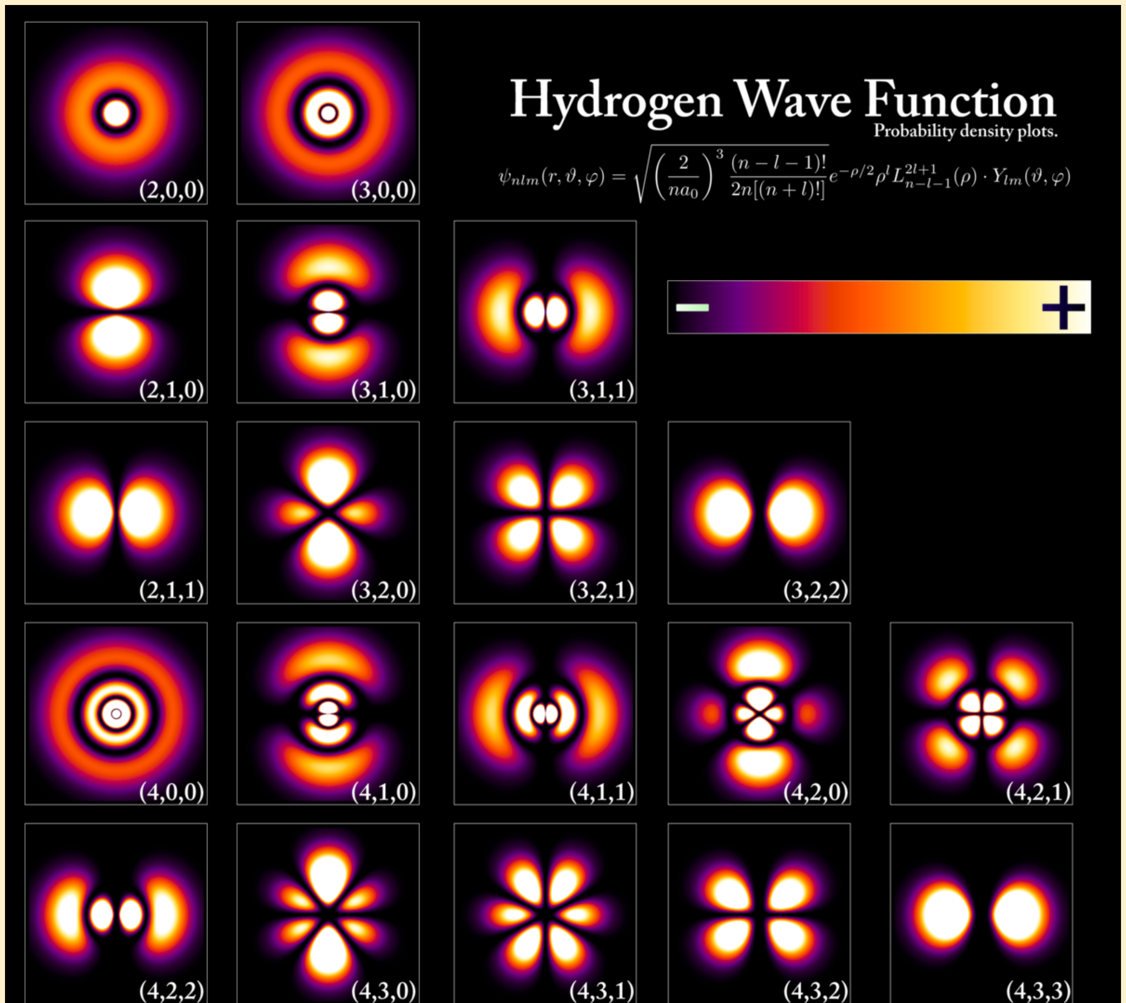
- **Grover's Algorithm** efficiently perform searches
- Quantum Physics for Medicine and Materials
- High Energy Particle Physics (Me!)

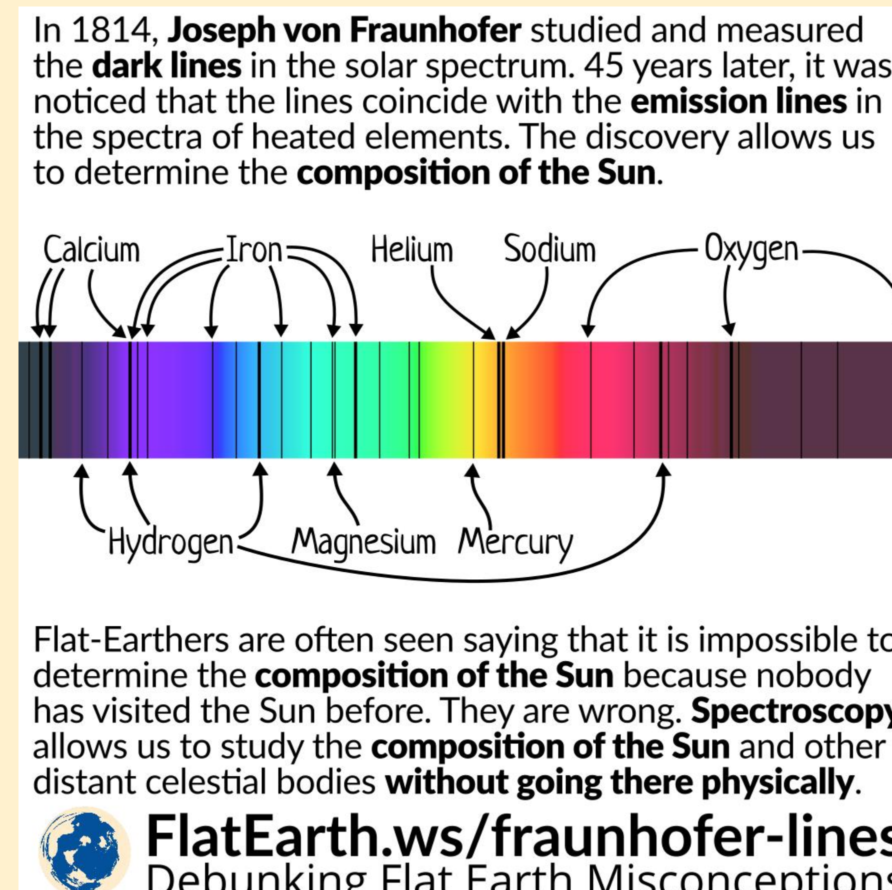


- *Not all problems have a faster quantum algorithm*
  - Can't sorting faster

What’s special about quantum mechanics? The quantum!

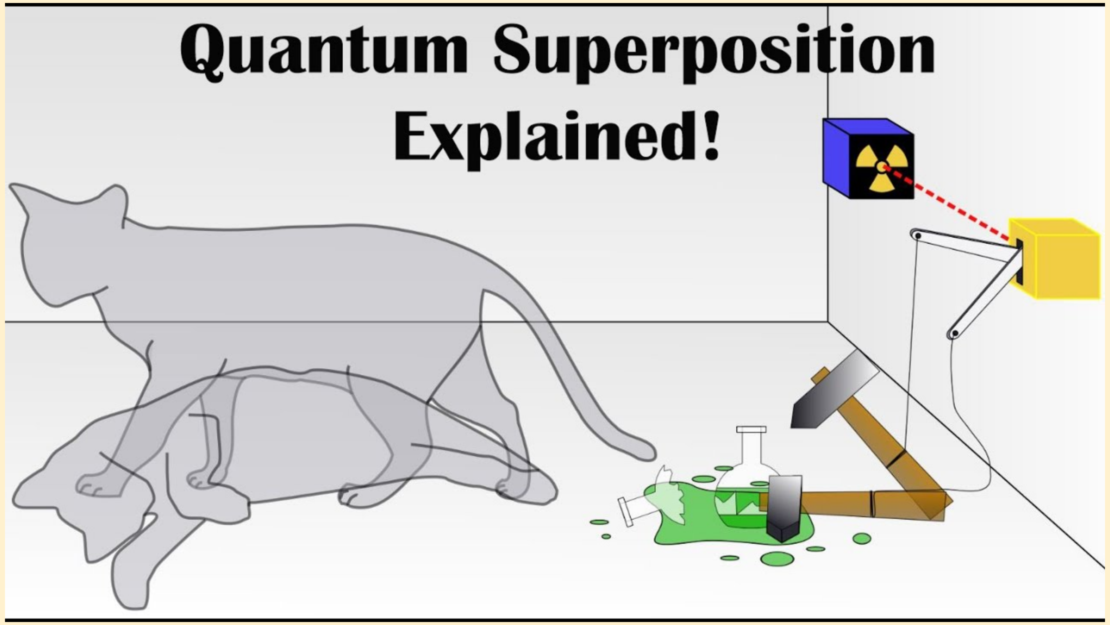
- Quantized states: Only specific values of properties (e.g. energy) are allowed





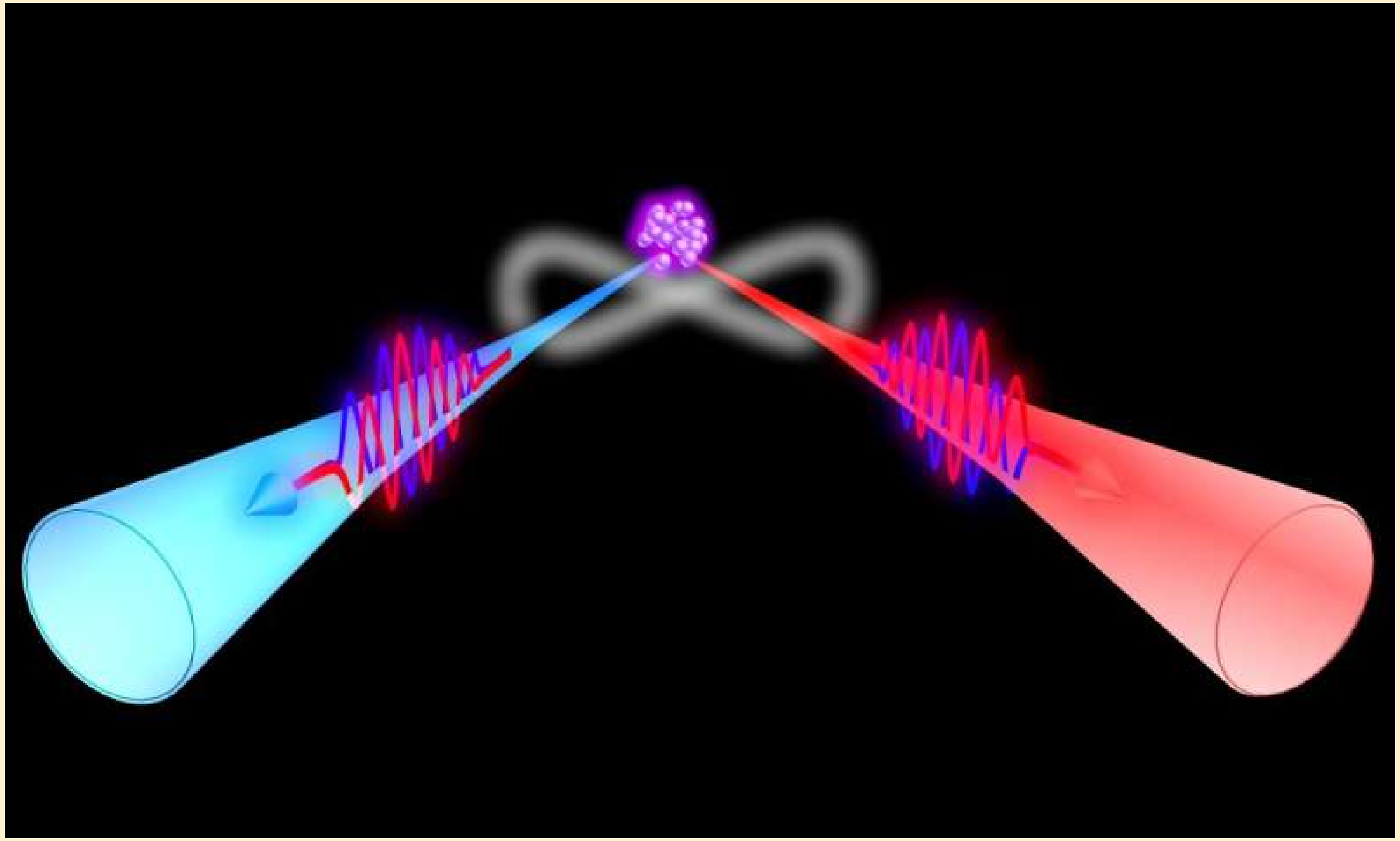
What's special about quantum mechanics? Superposition!

- Superposition: Systems can be in multiple states at once!
- Wave function is sum, $|\Psi\rangle = a|\Psi_a\rangle + b|\Psi_b\rangle$
- Amplitudes are complex numbers
- Upon *measuring,* $|\Psi\rangle$ "collapses" to a single state with probability e.g. $|a|^2$

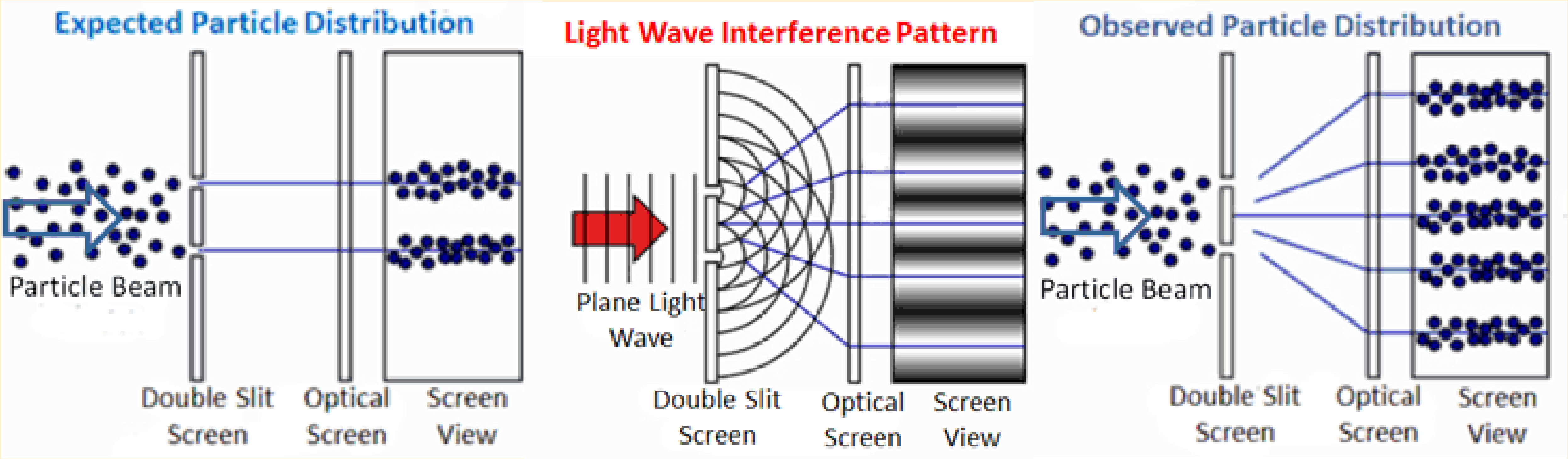


What’s special about quantum mechanics? Entanglement!

- Entanglement: States can’t be subdivided into single particle states
- Spooky action at a distance!

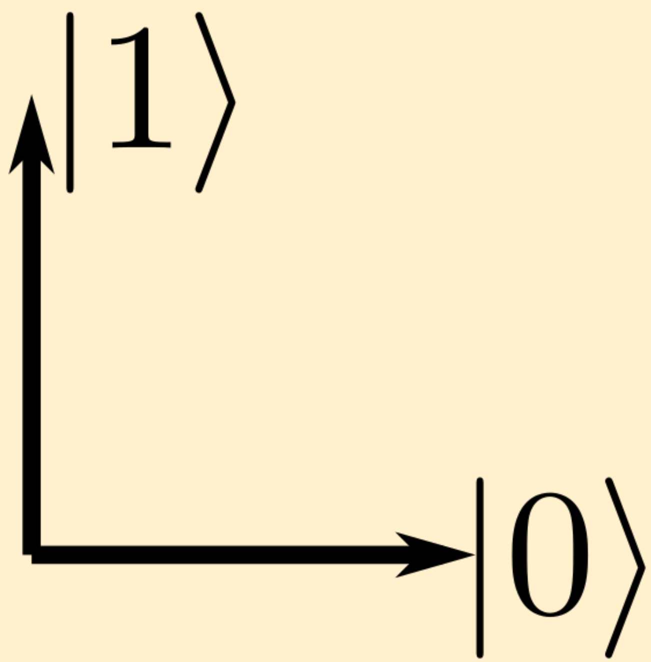


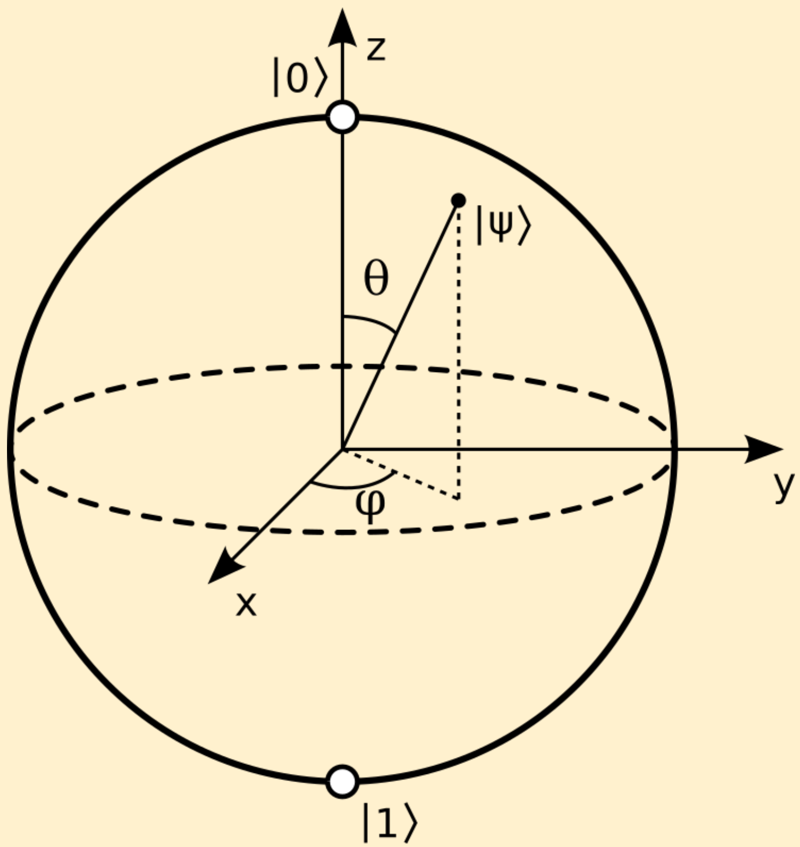
- Particle-Wave Duality: a "particle" behaves in wave-like ways like it can interfere with itself



How does a qubit differ from classical bit?

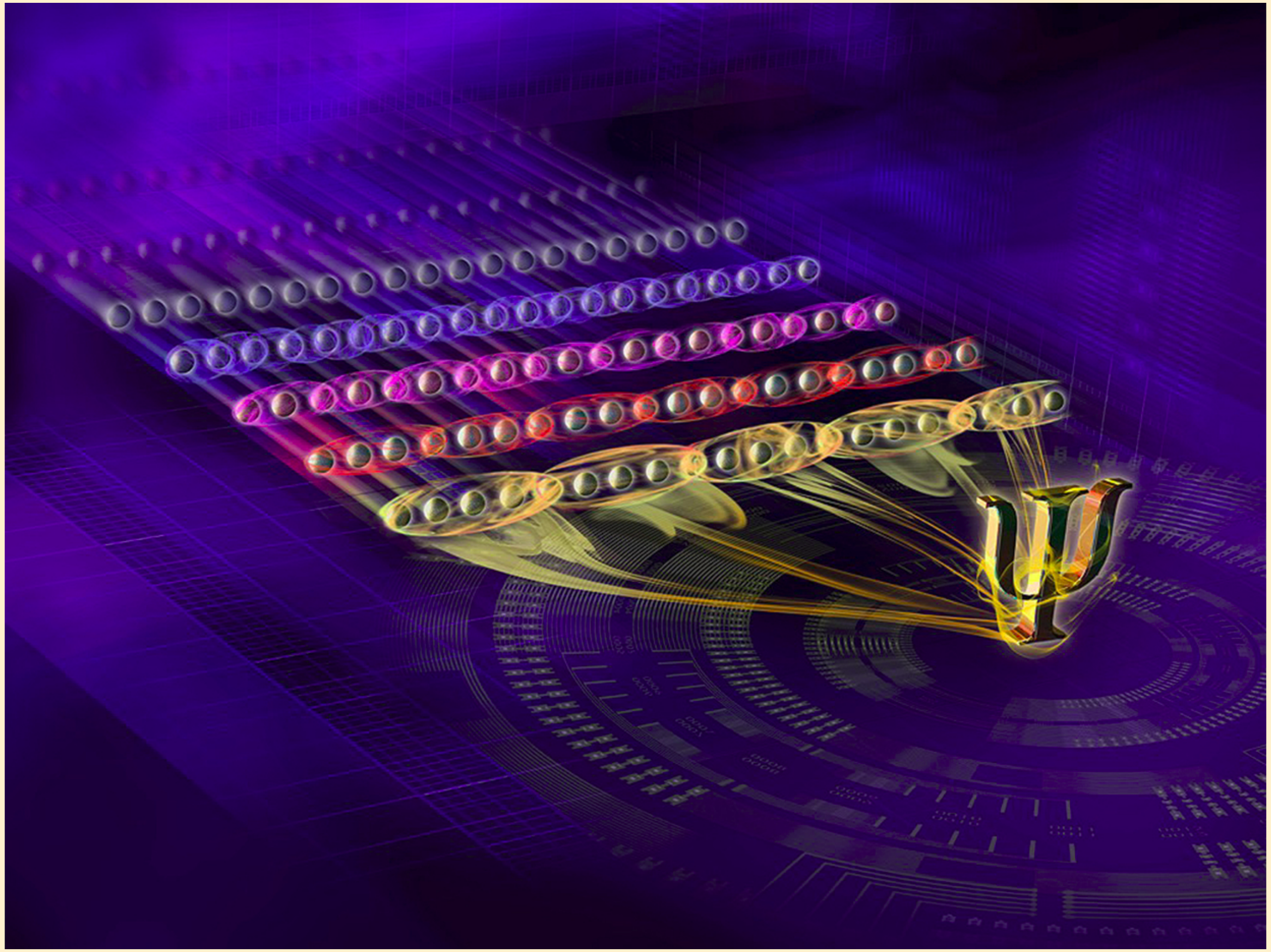
- Bit = {0,1}
- Qubit = a|0>+b|1>, a superposition!





How does a set of qubits differ from bits?

- Bits = {0,1}x{0,1}={00,01,10,11}
- Qubits = a|00>+b|01>+c|10>+d|11>, entangled!



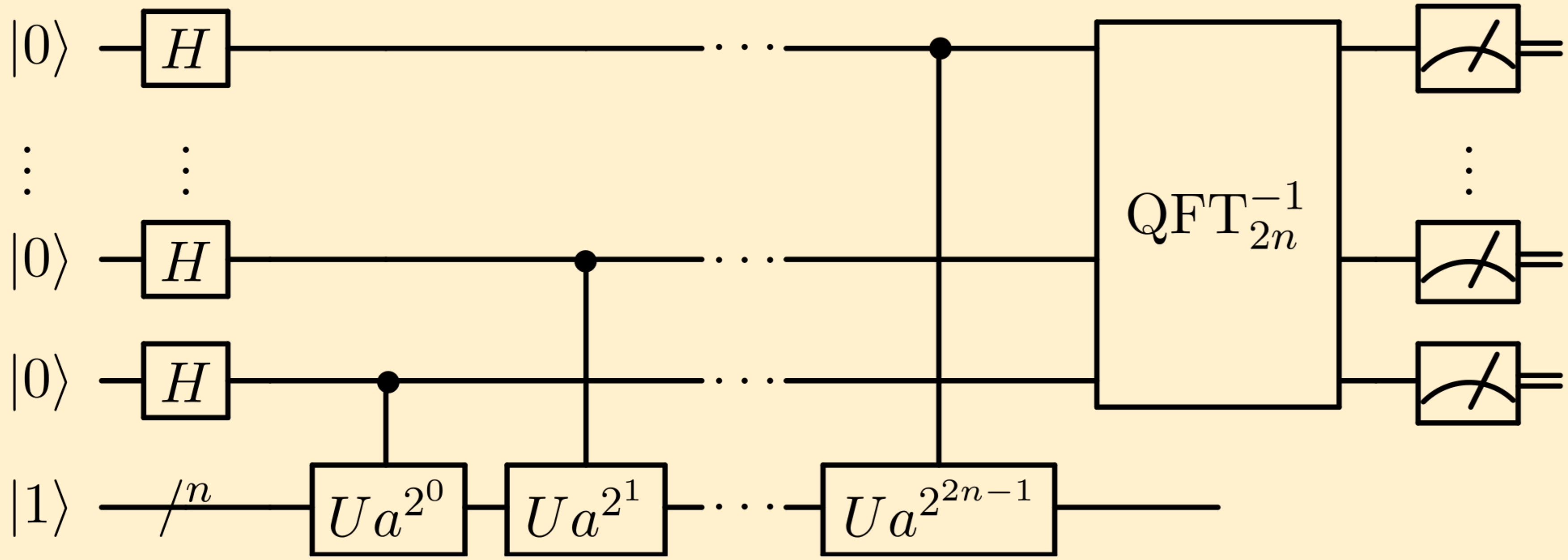
The basics of Quantum Information: Qubit storage

- For *n* qubits, there are then 2^*n* amplitudes
- Need 2^*n* complex numbers for |Ψ>
- For Google Sycamore (53 qubits) needs 1 PB~1000 TB
  - Human brain ~ 3 PB
  - World's largest supercomputer (Summit at Oak Ridge) ~ 10 PB

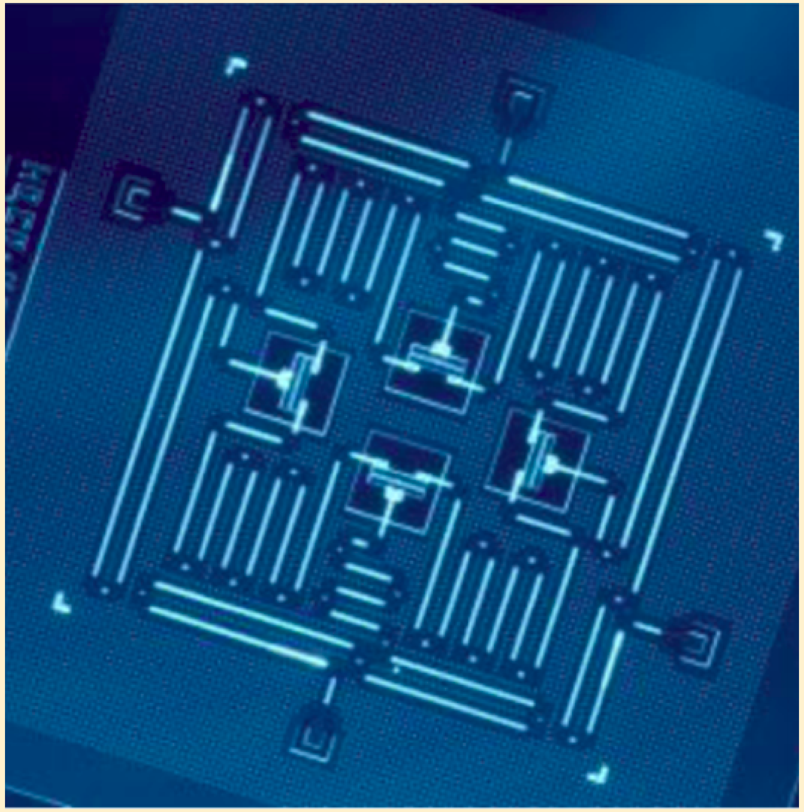
But, for small *n<20*, we can **classically** simulate the QC on a laptop. This is super useful for algorithm research!

Basics of quantum algorithms

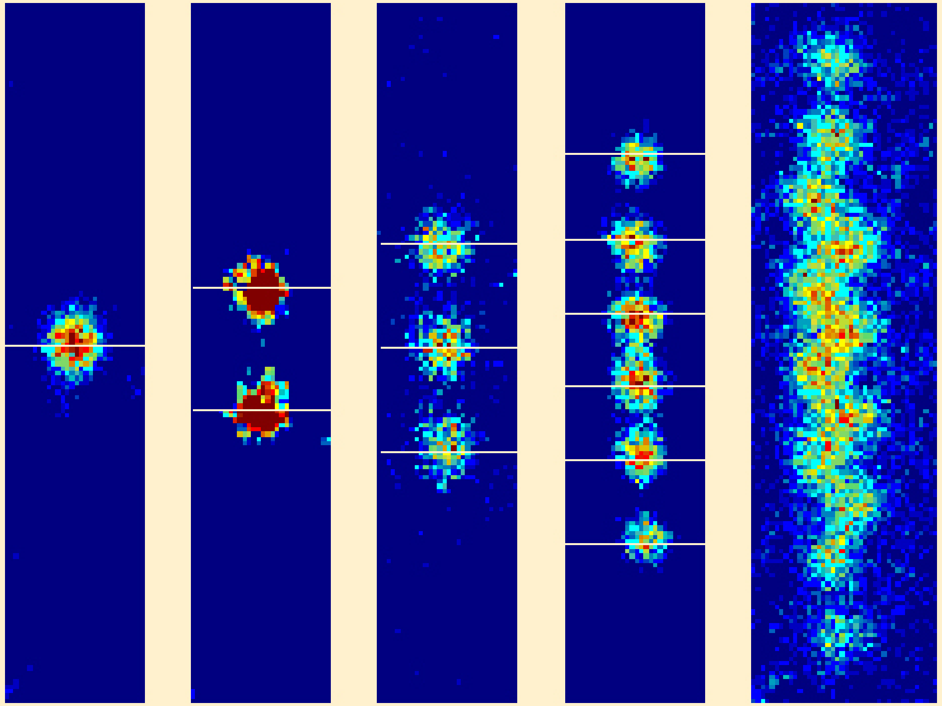
- Prepare the qubits into a **superposition**
- Act on qubits with **gates** that perform operation to preferentially amplify desired answers
- Measure qubits → Correct answer with some **probability**



What are they made from

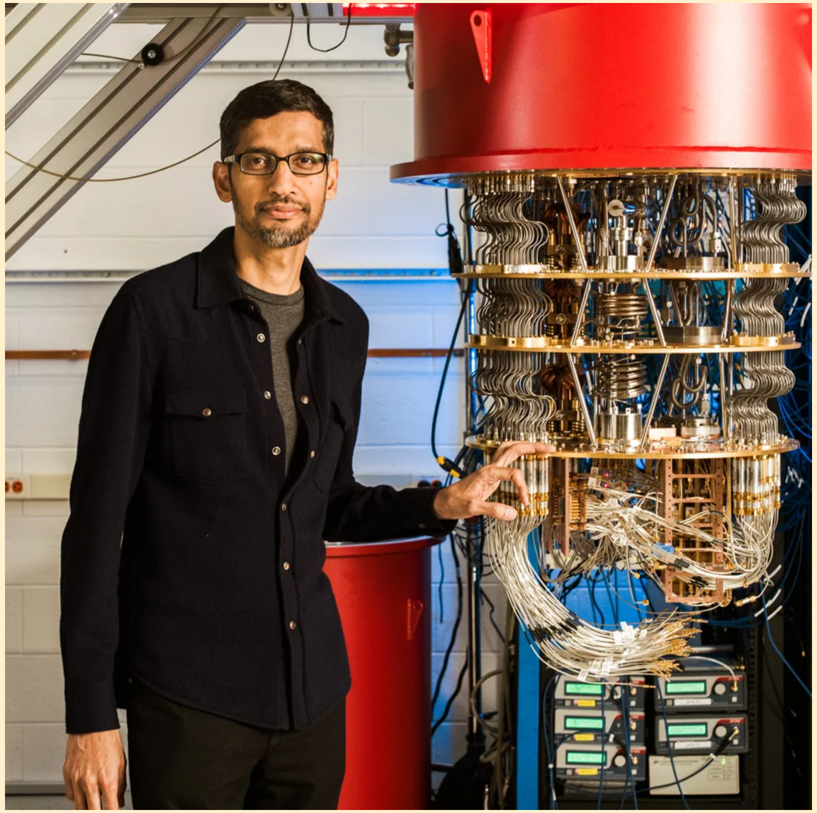


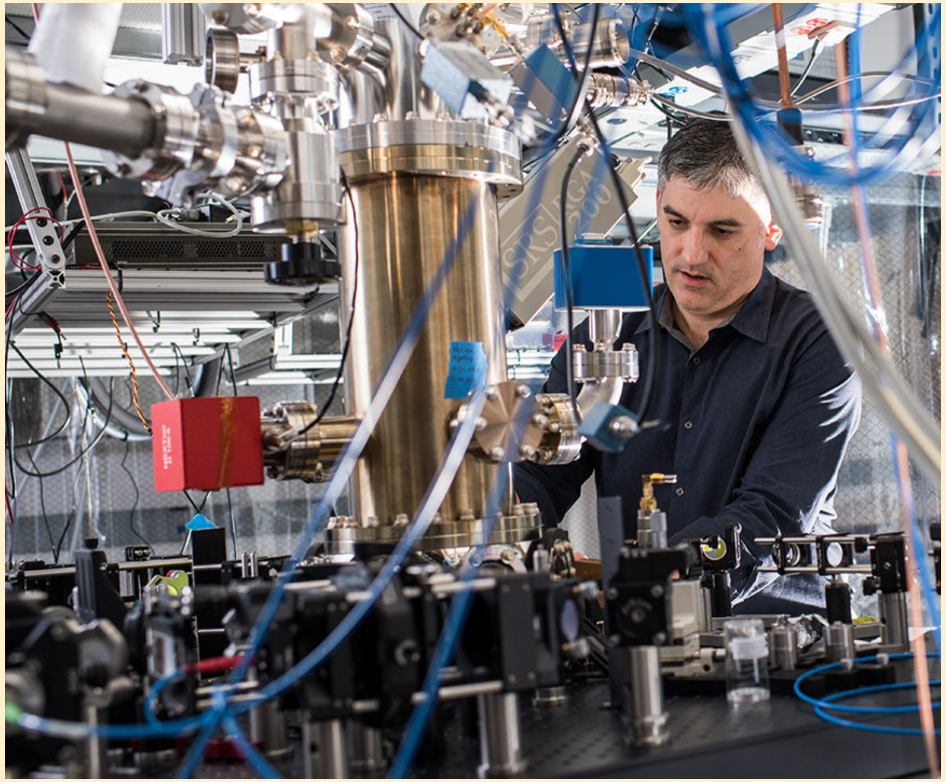
Superconducting Circuits



Cold Ions / Cold Atoms

What do they look like?

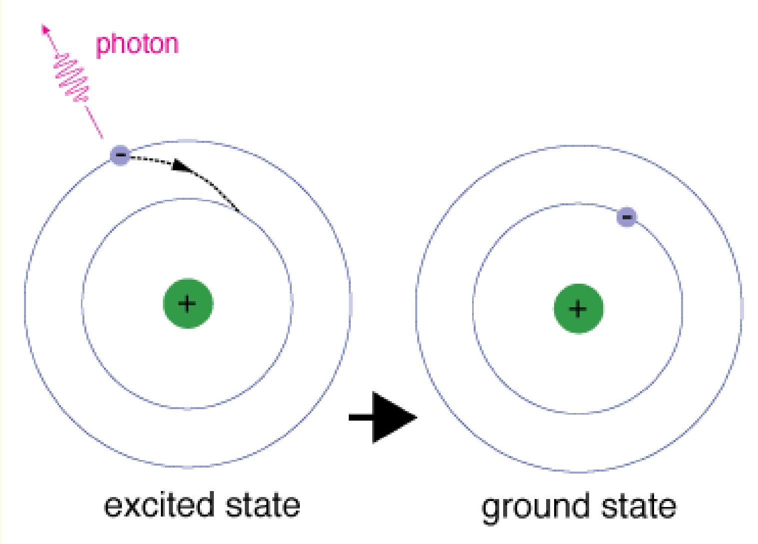


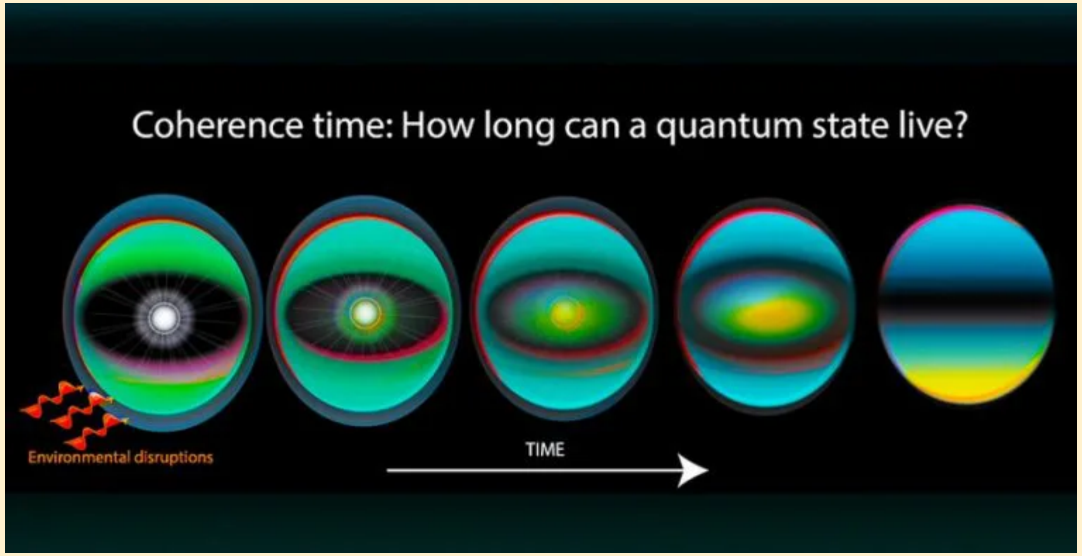


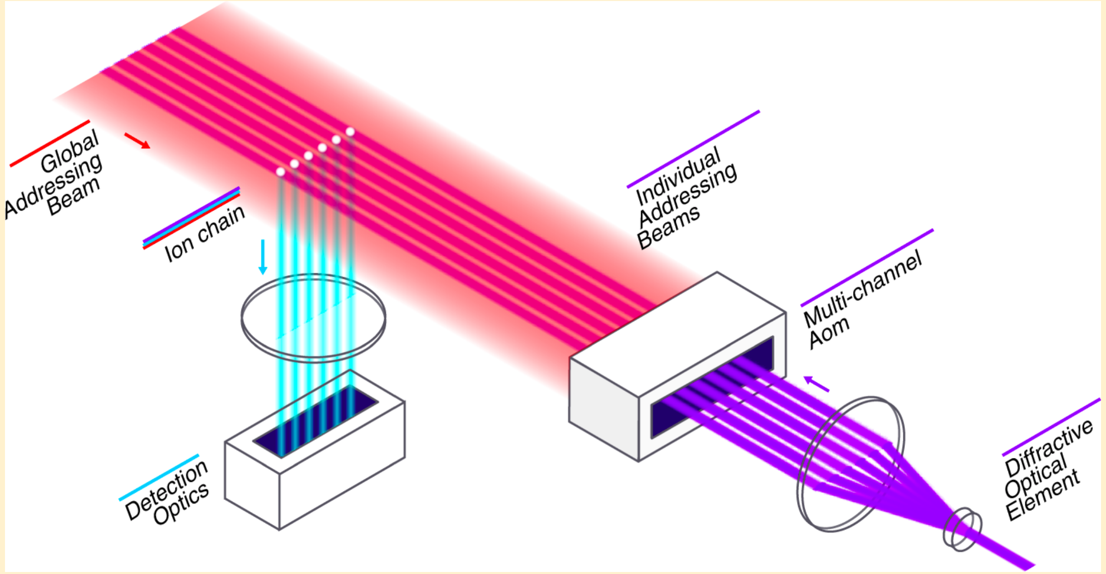
Why don't we have them today?

- Qubit ***"relax"*** to ground state: |1>→ |0>
- Outside world ***"heats"*** system: |11>+|00>→ |00>
- Fidelity: Gates ***aren't*** exact :

  Instead of U|0>→ |1>, U|0>→ (1-a)|1>+a|0>

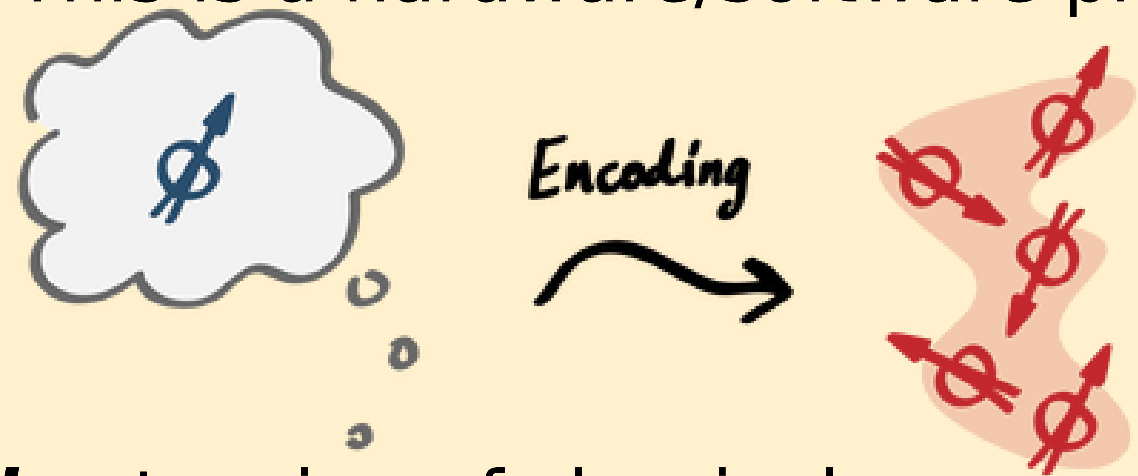




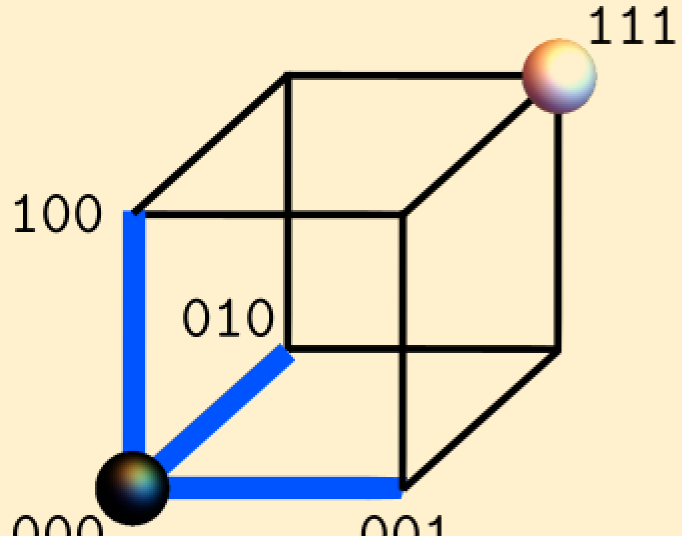


How do I make a better quantum computer?

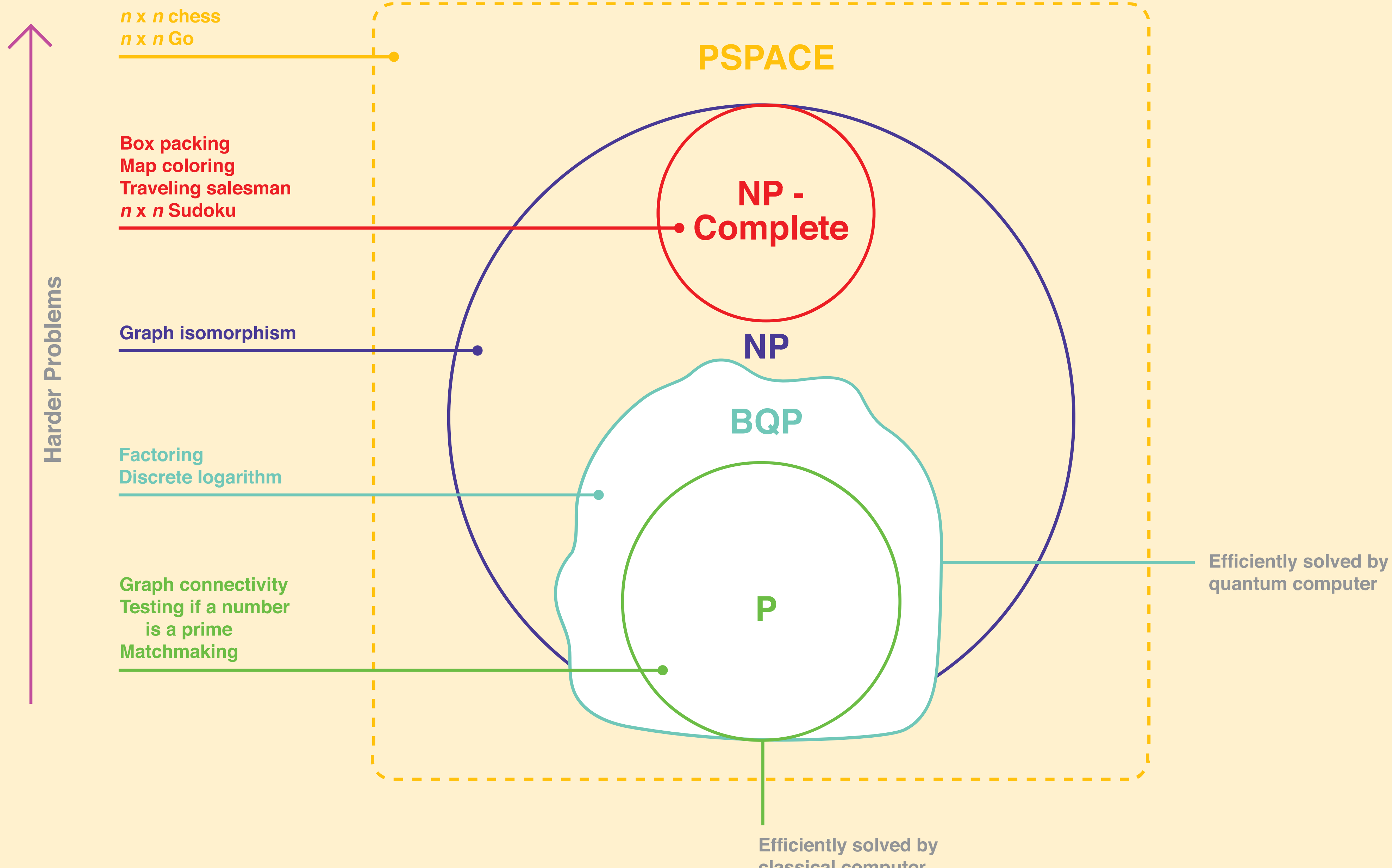
- Error Correction: Finding clever ways to overcome these limitations – This is a hardware/software problem



- A ***nontrivial*** extension of classical error correction



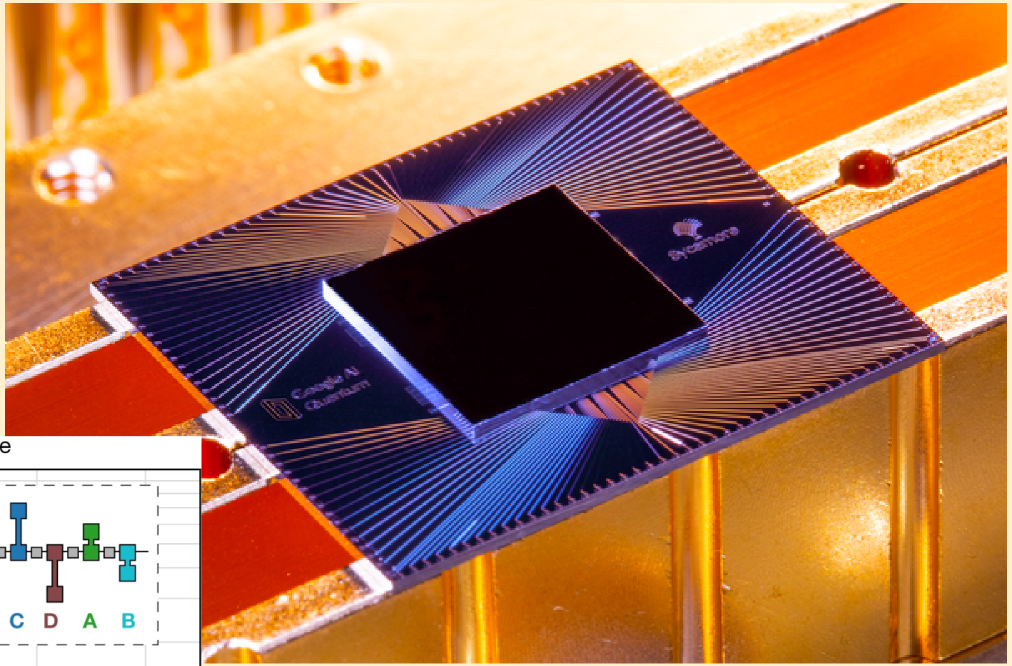
Quantum Complexity

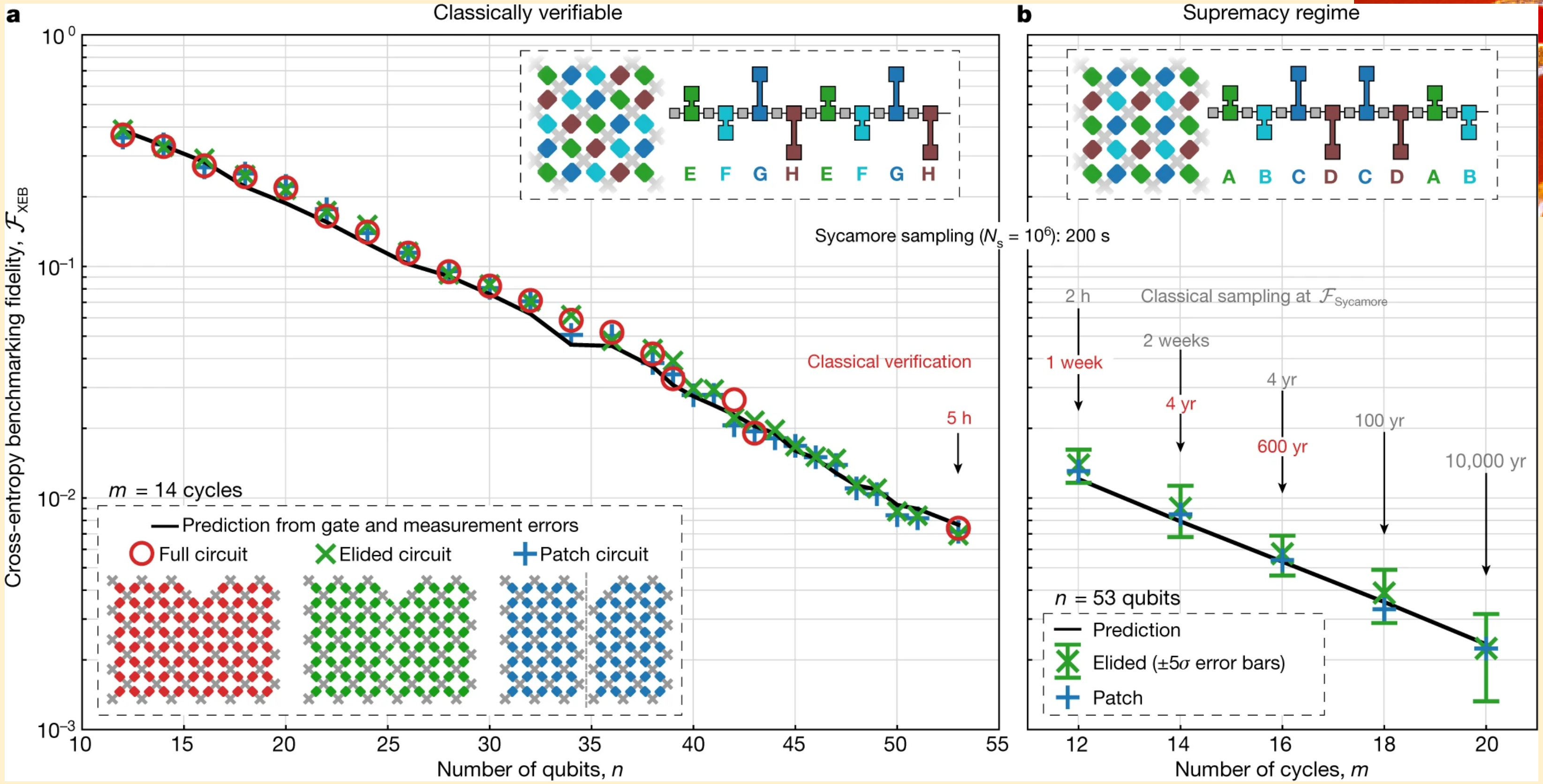


Quantum advantage

It may have already occurred

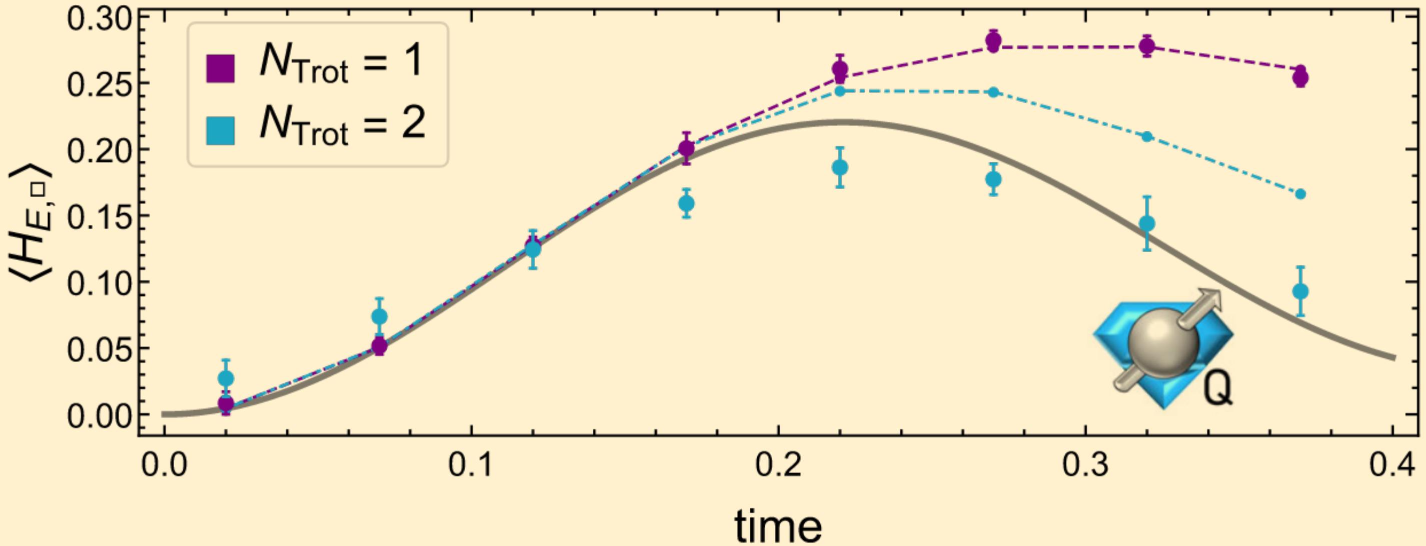
- Google Sycamore
- w/ Random Digit Classification





Noisy Intermediate Scale Quantum (NISQ) Era

- **NISQ Era:** ~100 Qubits, ~100 gates per qubit
- **Today:** ~10 qubits, ~10 gates per qubit
- Little/No error correction
- *Quantum Simulators* are critical



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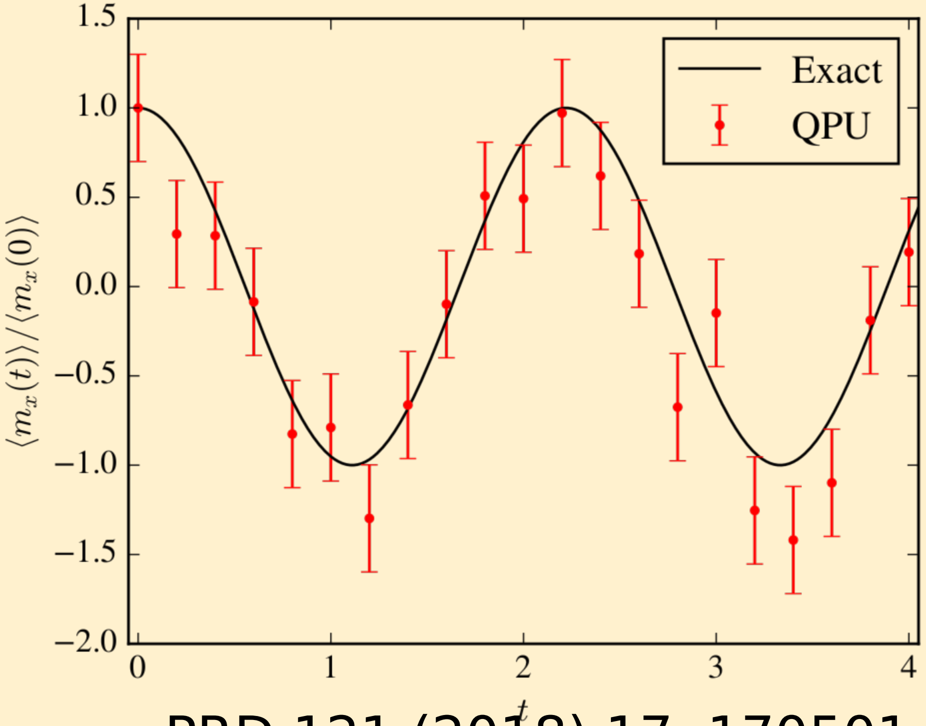

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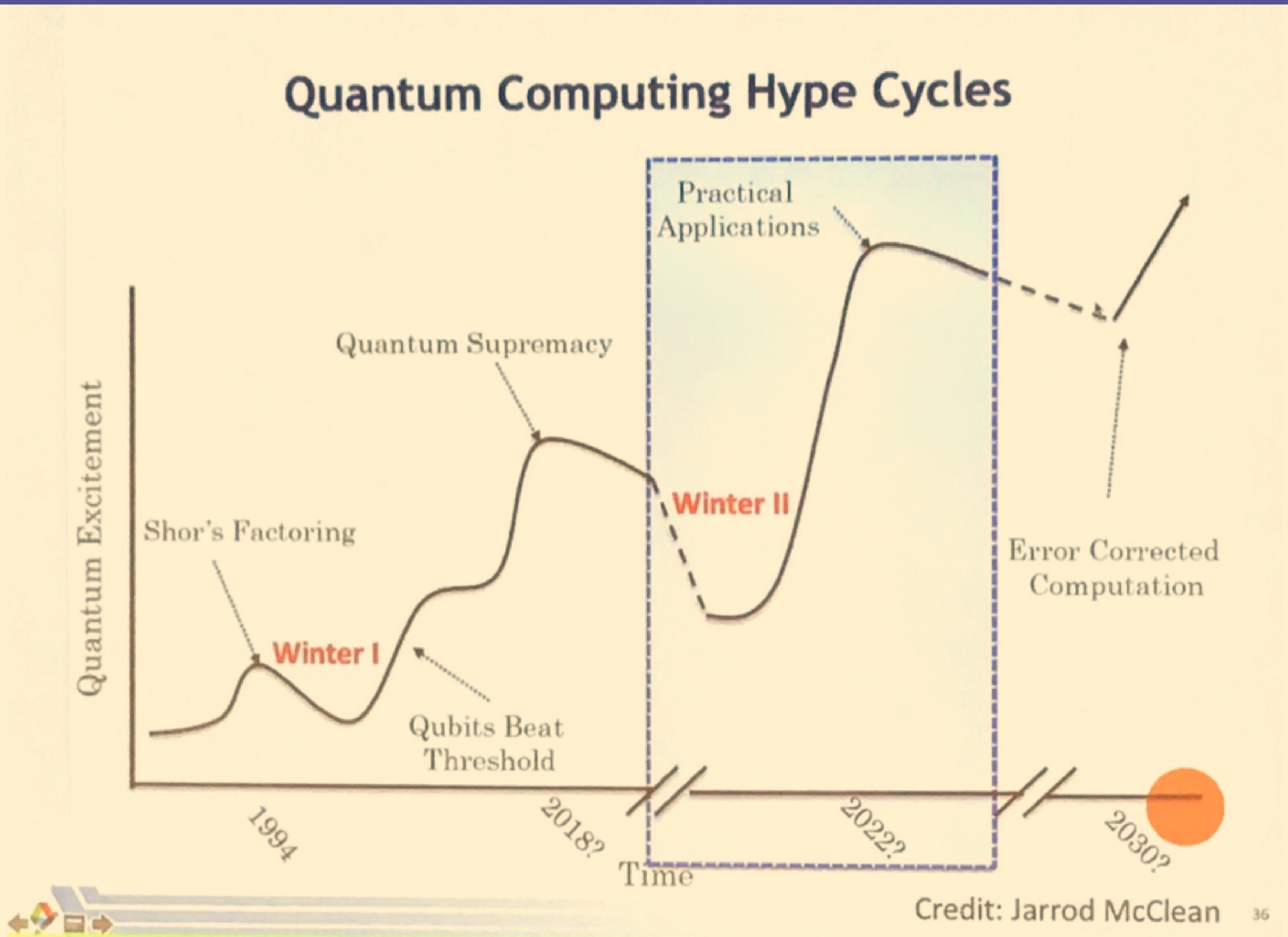
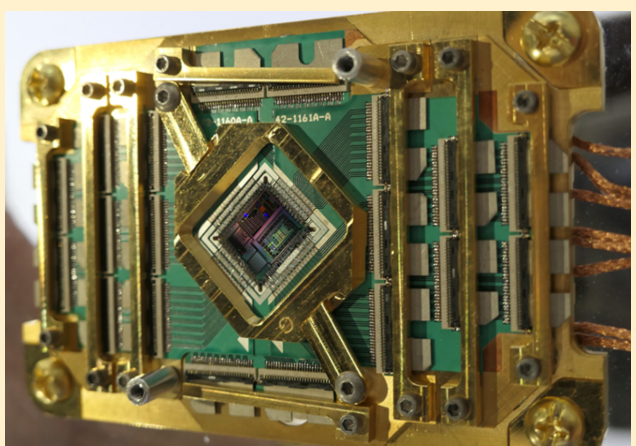
What is in the future?

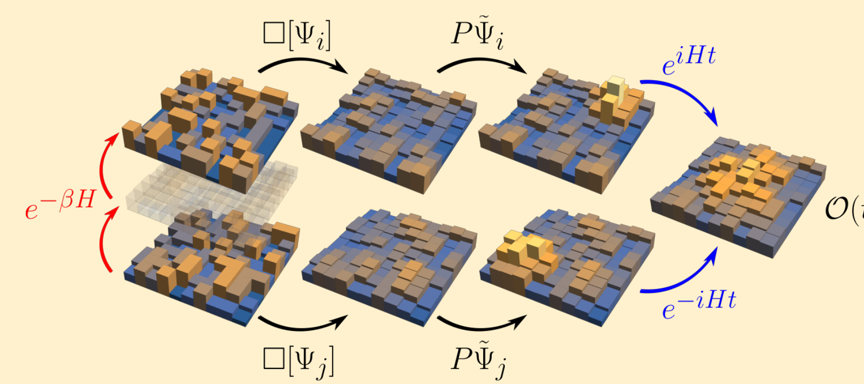


What can you, yes you, do?

- Design/experiment with hardware for better systems
- Develop code, compilers, and libraries for a completely new paradigm of computers
- Invent and analyze new algorithms for efficiently solve problems today and in the future



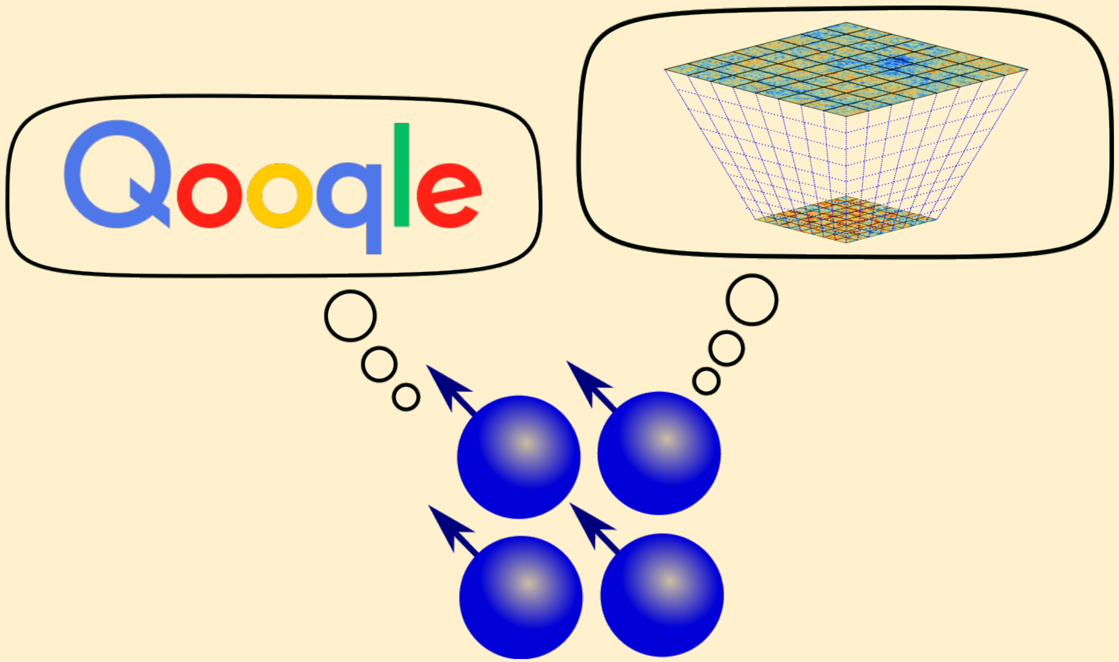
```python
from qiskit import QuantumProgram
qp = QuantumProgram()
qr = qp.create_quantum_register('qr', 2)
cr = qp.create_classical_register('cr', 2)
qc = qp.create_circuit('Bell', [qr], [cr])
qc.h(qr[0])
qc.cx(qr[0], qr[1])
qc.measure(qr[0], cr[0])
qc.measure(qr[1], cr[1])
result = qp.execute('Bell')
print(result.get_counts('Bell'))
```



Every one of these topics can use you, right now

We live in exciting times...

- QC is a ***new*** paradigm using quantum mechanics
- May not use them in your day-to-day, but they will revolution the world
- QC is “just starting” and will be active for decades



You should be excited about the future, but it won’t come without hard work