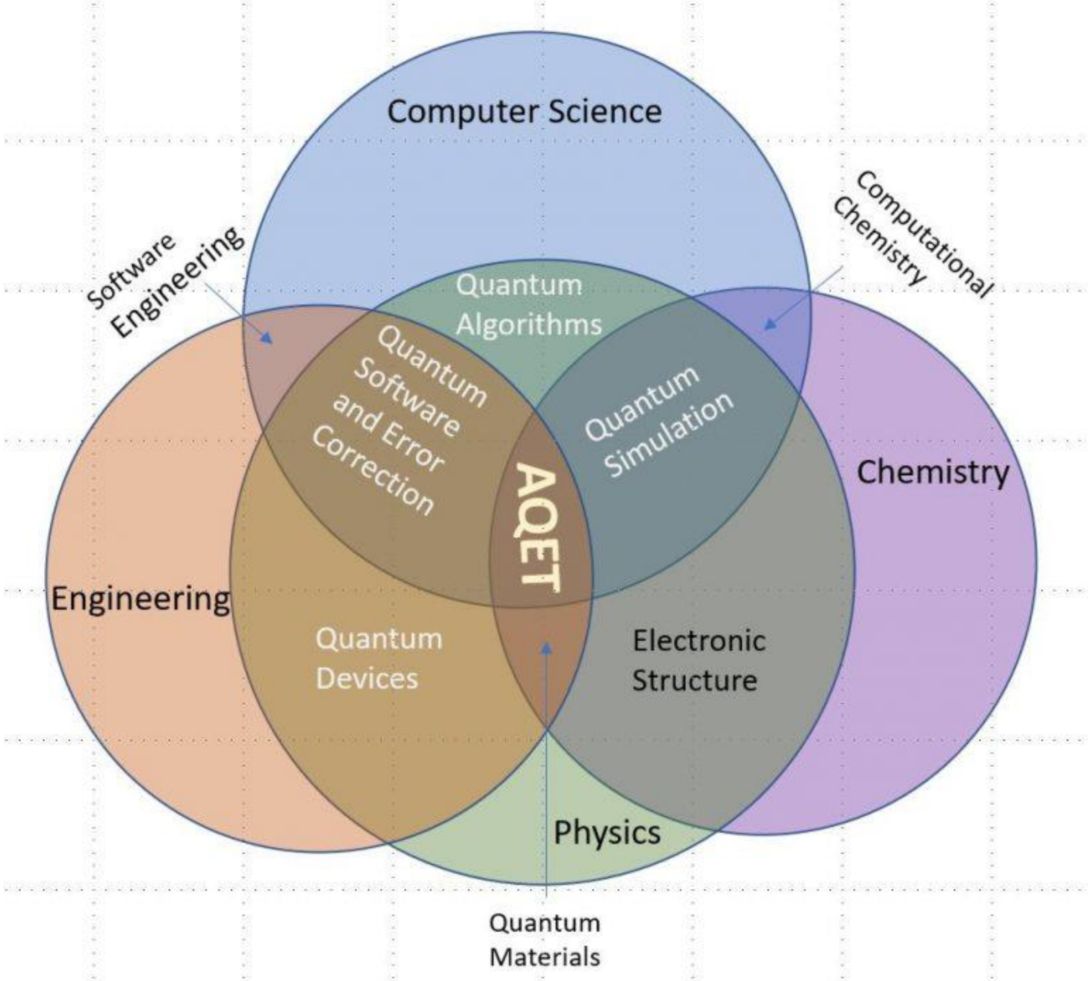
CHEM/MSE 561 Introduction

Prof. Brandi Cossairt

September 28, 2022

Accelerating Quantum Enabled Technologies (AQET) NRT



- **Course 1 (AU): Introduction to Quantum Information/Quantum Computing.** Three different course options will be offered, given the different domain-specific backgrounds of the students and the types of different research problems.
- **Course 2 (WI): Implementations in Quantum Information (CHEM 560).** A project-based course that highlights the challenges in implementing quantum information systems. The course combines the different skills sets to implement and characterize quantum information processing performance on IBM quantum computers using the Qiskit platform. Topics include quantum tomography, entanglement witnesses, randomized benchmarking, and quantum control. This course will be offered in Winter quarter.
- **Course 3 (SP): Advanced Topics in Quantum Information.** The third phase of the program, encompasses a range of domain-specific courses in advanced topics. Many different courses can satisfy this requirement.

Where are you? Intro to OISE for Chemists and

…epts of
…and
…natical

…ce,
…nd
materials systems.

What is a Qubit?

sensing
communication
computing } qubit

0

1

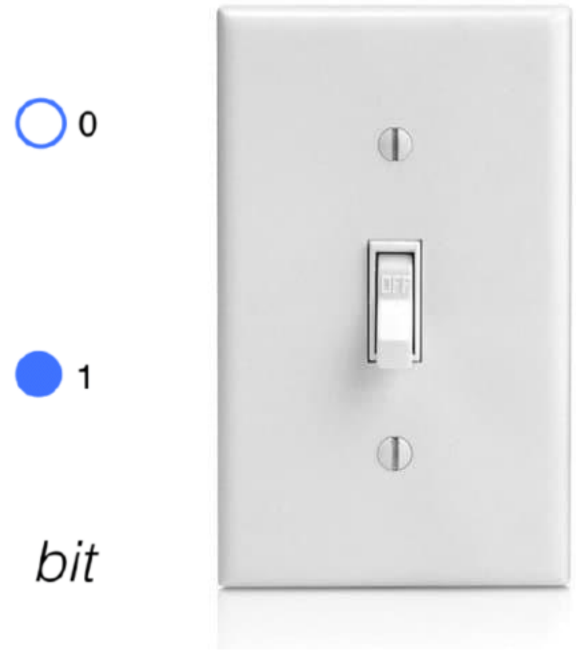
bit

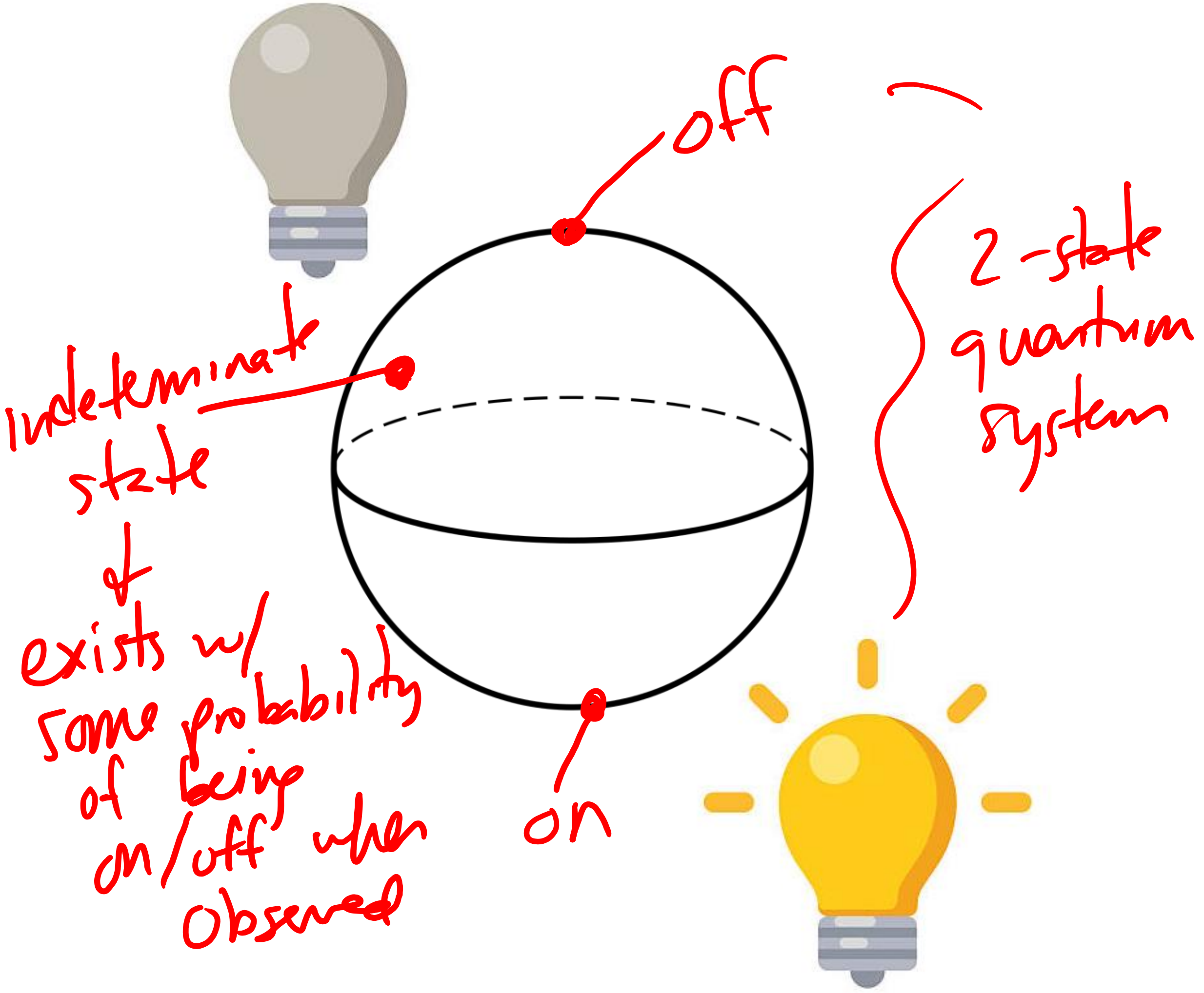
↳ binary digit

0/1
on/off
+/-
true/false

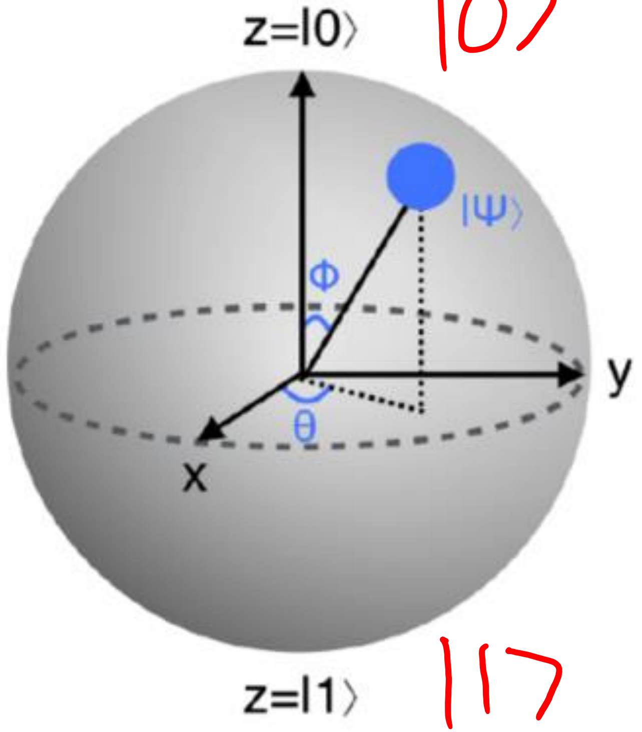
↑ correspondense to physical system defined by programmer

What is a Qubit?





A Qubit is Probabilistic



|0⟩

|1⟩

qubit

linear combinations of states

↪ superpositions

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

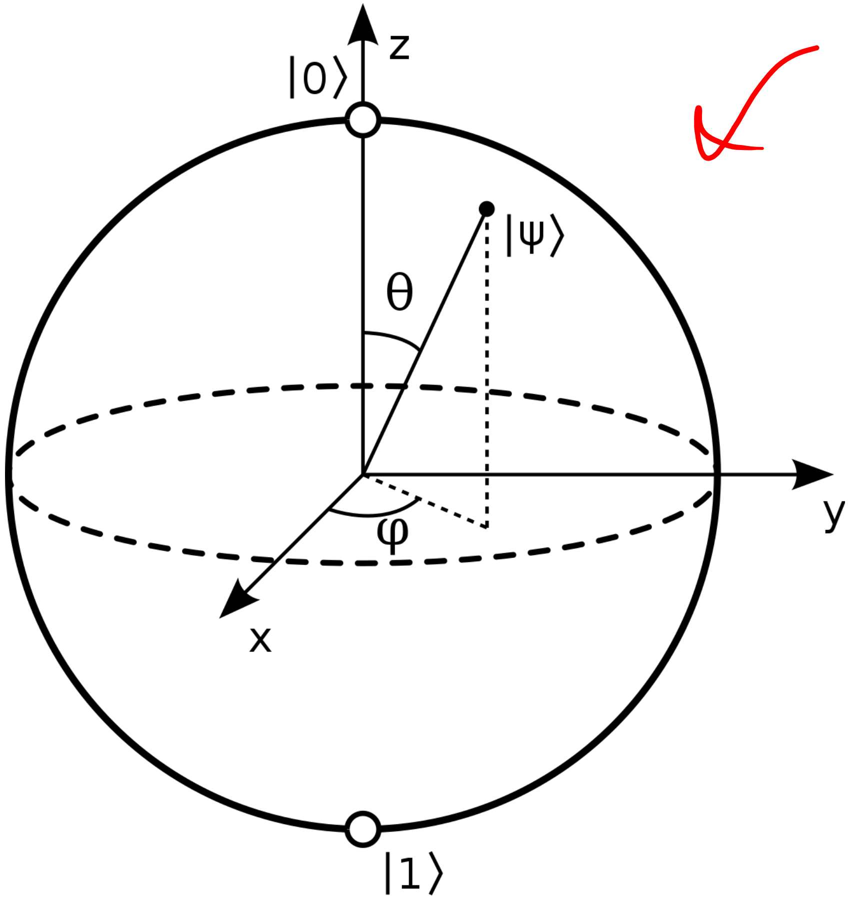
↖ state of qubit

$|0\rangle$ w/ probability $|\alpha|^2$

$|1\rangle$ w/ probability $|\beta|^2$

} sum 1

The Bloch sphere



✓ $|\alpha|^2 + |\beta|^2 = 1$

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

polar coordinates

θ, φ

Bits to Qubits…It's Exponential!

# of qubits	# bits / # loops	RAM	Time
13	8192	1 kB	$2.73\text{x}10^{-6}$ s
20	1048576	128 kB	$3.5\text{x}10^{-4}$s
23	8388608	1 MB	$2.8\text{x}10^{-3}$s
33	8589934592	1 GB	2.9 s
43	$8.8\text{x}10^{12}$	1 TB	49 mins
53	$9.0\text{x}10^{15}$	1 PB	35 hours
63	$9.2\text{x}10^{18}$	1 EB	97.5 years
1000	$1.1\text{x}10^{301}$	$1.3\text{x}10^{282}$ EB	$1.1\text{x}10^{284}$ years

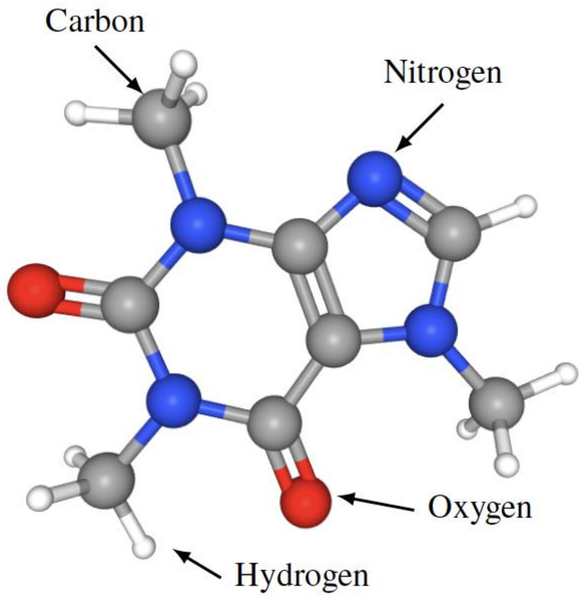
← 3 GHz

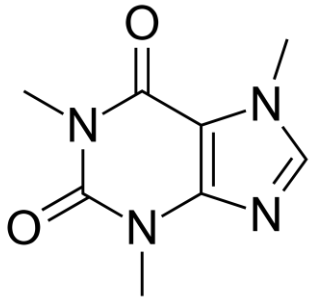
2 bits
0 0
0 1
1 0
1 1

n qubits
⇓
2^n bits

So What? The case of 1,3,7-trimethylxanthine

caffeine, 24 atoms





8 oz, 95 mg → 2.95×10^{20} molecules

10^{49}-10^{50} atoms on the planet

24 atoms → 10^{48} quantum states

↳ 10^{48} bits

160 qubits → 2^{160} bits $= 1.46 \times 10^{48}$ bits

Course outline

- Week 1: [Cossairt] What is Quantum Information Science and Engineering?
- Week 2: [Pauzauskie] Applications and Challenges: Quantum sensing, Communication, Computing
- Week 3: [Pauzauskie / Sutor Ch. 2-6 (5*)] Math Bootcamp: Imaginary Numbers and Linear algebra
- Week 4: [Pauzauskie / N&C Ch. 2] Intro to Quantum mechanics
- Week 5: [Cossairt / Sutor Ch. 7] One Qubit
- Week 6: [Cossairt / Sutor Ch. 11 and N&C Ch. 8] What Does it Take to be a Qubit? The relationship between material properties and quantum memory/quantum coherence
- Week 7: [Cossairt / Sutor Ch. 8-9] Entanglement and multi-qubit gates
- Week 8-11: [Cossairt & Pauzauskie]: Qubits and Material Systems
  - Guest Lecture **Stefan Stoll** (UW Chemistry), Wednesday 11/16
  - Guest Lecture **Kai-Mei Fu** (UW Physics), Wednesday 11/30
  - Guest Lecture **Arka Majumdar** (UW ECE), Wednesday 12/7

Course logistics

- Canvas Site – https://canvas.uw.edu/courses/1604983

- Assessment – weekly reading quizzes (30%), self-graded homework (30%), my favorite qubit project (working in teams, 30%), participation and discussion (10%)
- Weeks 1 – 8ish: Monday, Wednesday = lecture; Friday = reading quiz, discussion, and problems
- Week 8ish – 11 = Monday = student presentations; Wednesday = Guest lecture; Friday = reading, discussion, and problems

My favorite qubit team project and presentation

- Teams of 2-3
- Write 1 question and provide answer for PS 4 (w/ PS 2)
- Infographic (w/ PS 3)
- 20-minute presentation + Q&A (Weeks 8-11)
- History, current status, research and implementation challenges, prospects

Options:

- superconducting qubits
- trapped atoms/ions
- spin qubits
  - classic solid state/epitaxial qubits
  - designer defects (diamond, silicon, etc.)
  - molecular qubits
- optical (single photon) qubits
- topological qubits

Canvas qubit references: https://canvas.uw.edu/courses/1604983/files/folder/Reading%20Materials/Qubits

The Quantum Daily's Quantum Computing Company Market Map

THE QUANTUM DAILY
QUANTUM COMPUTING AND BEYOND

QCs	Superconducting	Trapped Ion	Photonics	Neutral atoms	Silicon	Other
Americas	rigetti IBM Q Google AI Quantum D-Wave The Quantum Computing Company (Quantum Annealing) qci intel	Honeywell IONQ	PsiQuantum XANADU	ATOM COMPUTING QuEra Cold atom	intel	EeroQ [Electrons on Helium] Microsoft Topological
EMEA	OQC	AQT				
APAC	Alibaba.com				Silicon Quantum Computing	

www.thequantumdaily.com

Week 1 Reading

- Sutor Chapter 1
- N&C Chapter 1
- National Strategic Overview for Quantum Information Science (September 2018)
  - https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
- NSF QISE Research Page
  - https://www.nsf.gov/mps/quantum/quantum_research_at_nsf.jsp

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

https://www.science.org/doi/10.1126/science.354.6316.1090

https://thequantuminsider.com/2022/09/05/quantum-computing-companies-ultimate-list-for-2022/

Photonic Quantum Computing: https://thequantuminsider.com/2022/03/24/6-quantum-computing-companies-working-with-photonic-technology/

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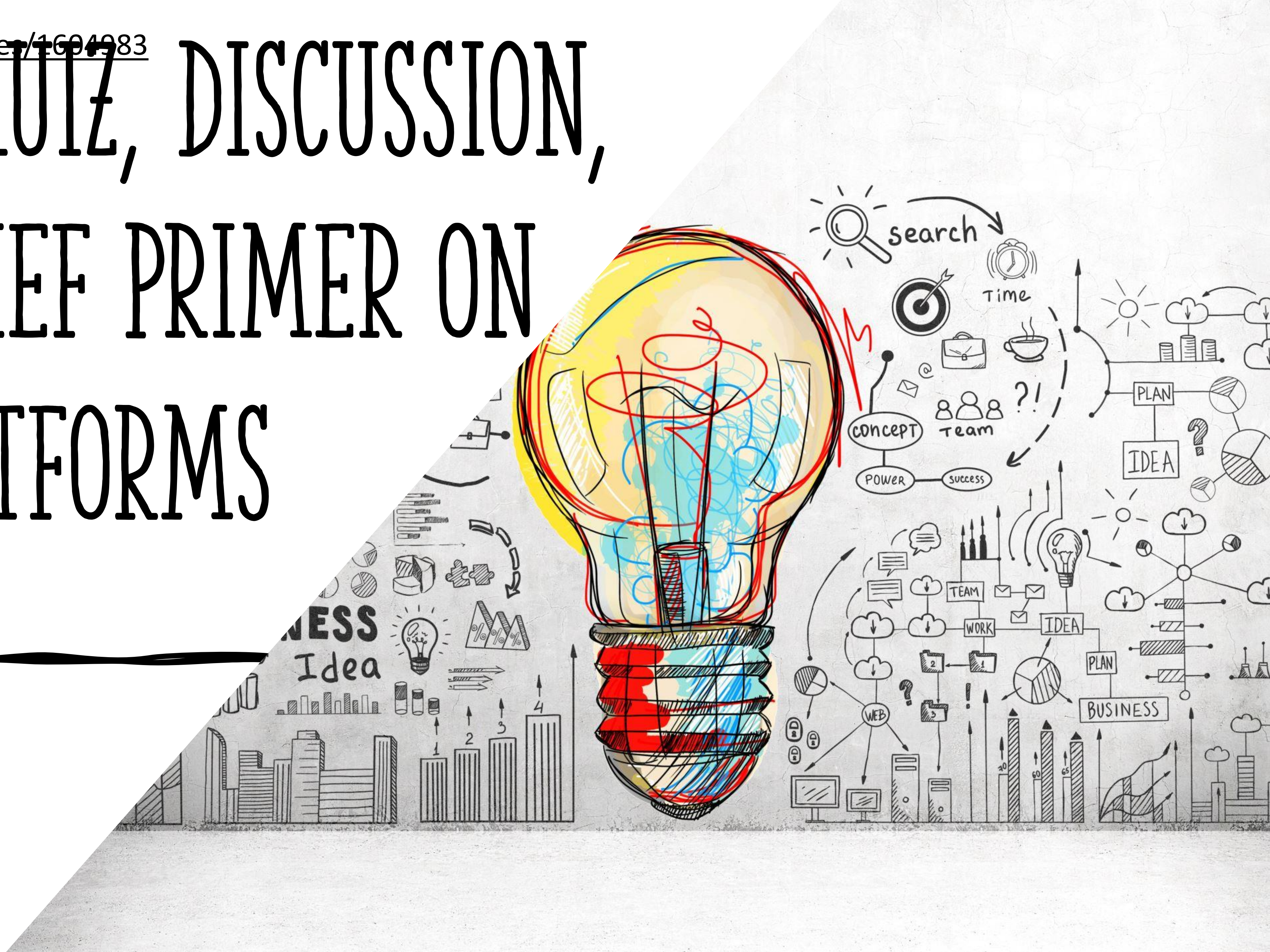
READING QUIZ, DISCUSSION, AND A BRIEF PRIMER ON QUBIT PLATFORMS



Prof. Brandi Cossairt

9/30/2022

CHEM/MSE 561 LEARNING CONTRACT

In CHEM/MSE 561 we seek to build community, share knowledge, and create a foundation of support. We will work together to support and learn from our peers. We commit to:

- **Be prepared and engaged** - come to class having reviewed and reflected on the reading. Actively contribute to the discussions and engage with guest speakers.
- **Ask for help** - from each other and the larger UW QISE community - we do not expect to be the source of all information. We will proactively help students find the resources they need.
- **Accessibility** - accommodate students' needs and ensure format of class is given in a way that caters to all learning types, recognizing that we all come from different backgrounds.
- **Be patient** - Grappling with the topics in this course can be challenging. Remember to give one another the space and time to think and reflect. Silence is OK.

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

- Quantum-smart workforce
- Noisy intermediate scale quantum technology
- Quantum essential supporting technologies: cryogenics, photonics, low-noise microwave amplifiers, nanofabrication
- Areas of QIS are limited by unavailability of specialized materials and advanced characterization and fabrication technologies
- QIS motivators: military capability, economic productivity, international competitiveness

QUBIT PLATFORMS

- superconducting qubits
- trapped ions; neutral atoms
- spin qubits
  - classic solid state/epitaxial qubits
  - designer defects (diamond, silicon, etc.)
  - molecular qubits
- optical (single photon) qubits
- topological qubits

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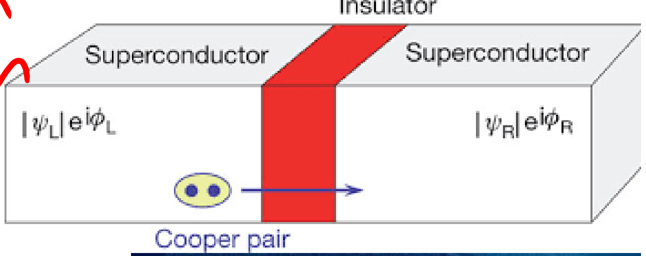
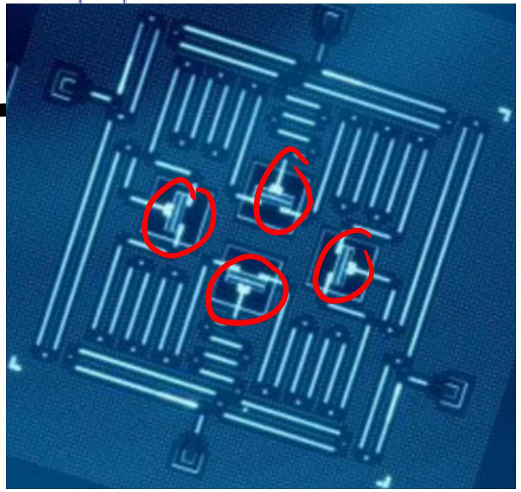
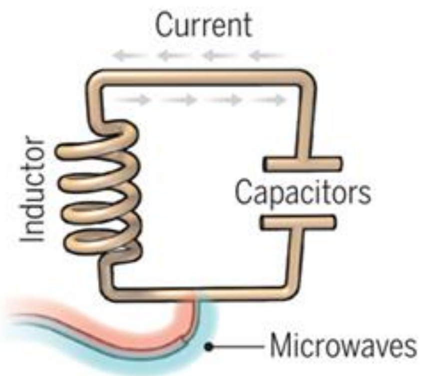
EMEA	OQC	AQT				
APAC	Alibaba.com				Silicon Quantum Computing	

SUPERCONDUCTING QUBITS

Josephson Junction







→ e- in cooper pairs (bound e- pairs)
↳ no resistance
↳ Al, 1.2 K

⇒ one quantum wavefunction

① charge qubit → amplitude

② flux qubit → phase

Q: are cooper pairs interacting?

Superconducting loops

A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.

Longevity (seconds)
0.00005

Logic success rate
99.4%

Number entangled
9

Company support
Google, IBM, Quantum Circuits

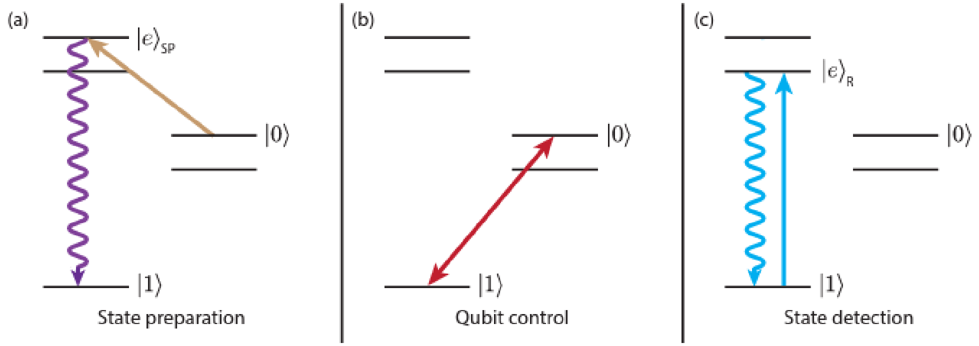
Pros
Fast working. Build on existing semiconductor industry.

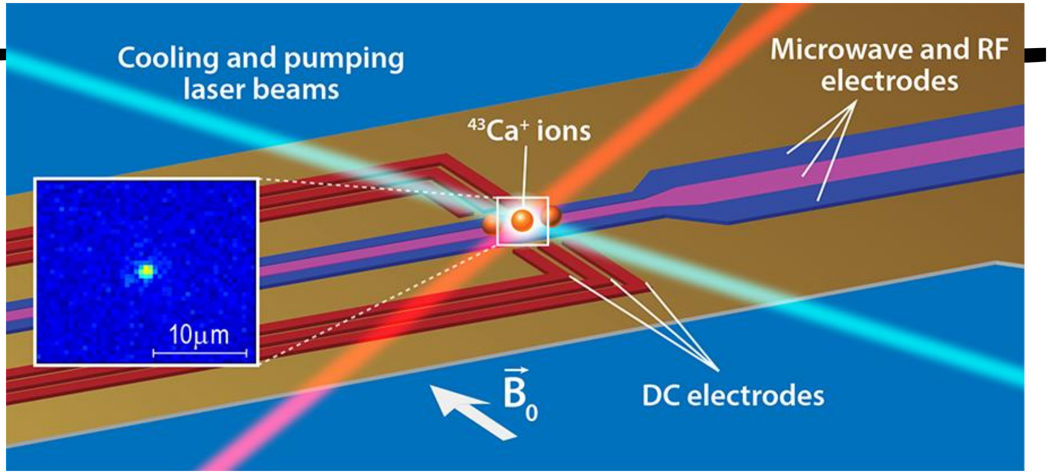
Cons
Collapse easily and must be kept cold.

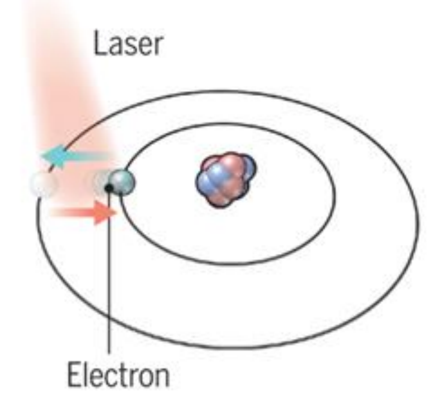
Disadvantage: scaling

Advantages: long coherence times
all identical
few additional states

TRAPPED IONS







Trapped ions

Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

>1000

99.9%

14

ionQ

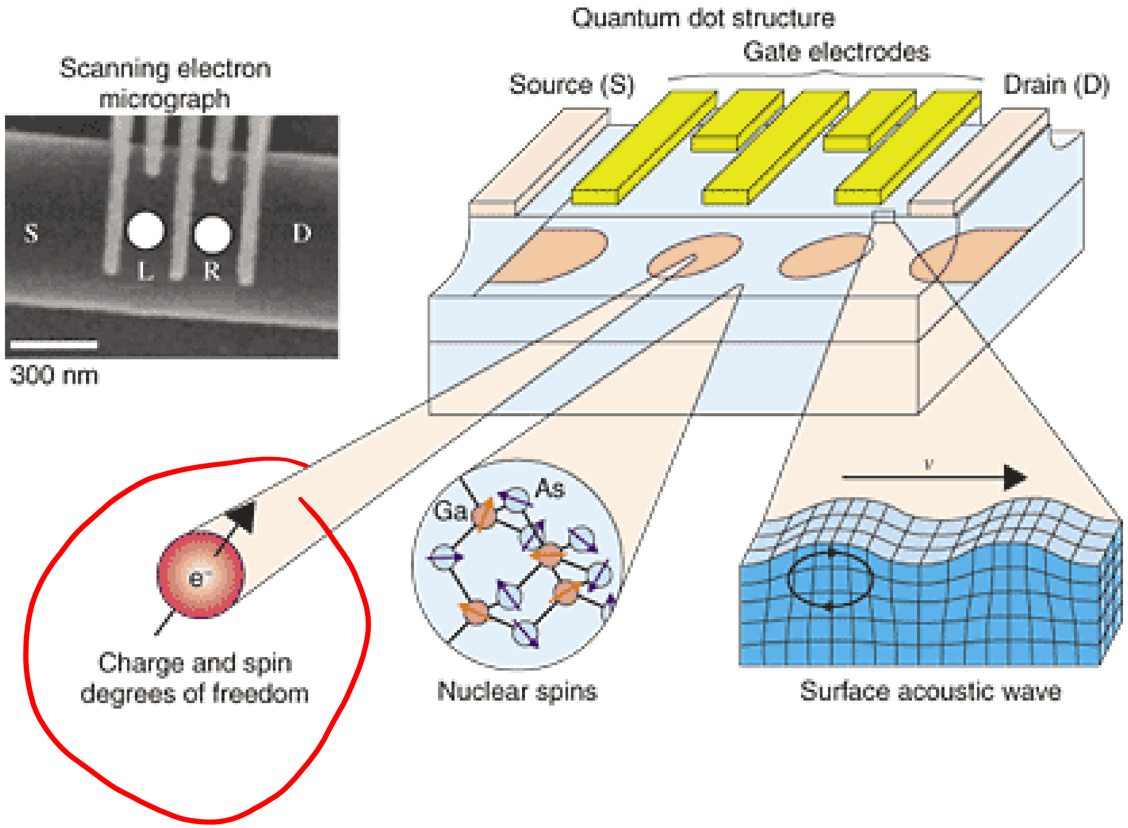
Very stable. Highest achieved gate fidelities.

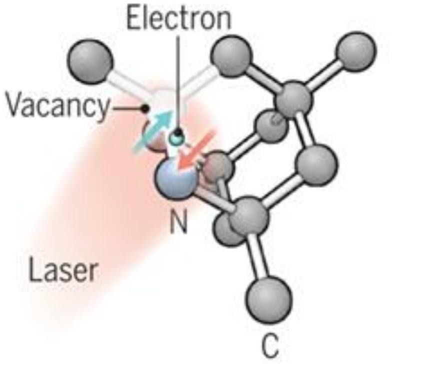
Slow operation. Many lasers are needed.

1. Hyperfine qubits ΔE GHz
2. Zeeman qubits (magnetic sublevels) ΔE 10s MHz
3. Fine structure qubits ΔE 10s THz
4. optical qubits (optical transition) ΔE 100s THz

SPIN QUBITS

- Solid state QDs (GaAs, Si)





Diamond vacancies

A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

10

99.2%

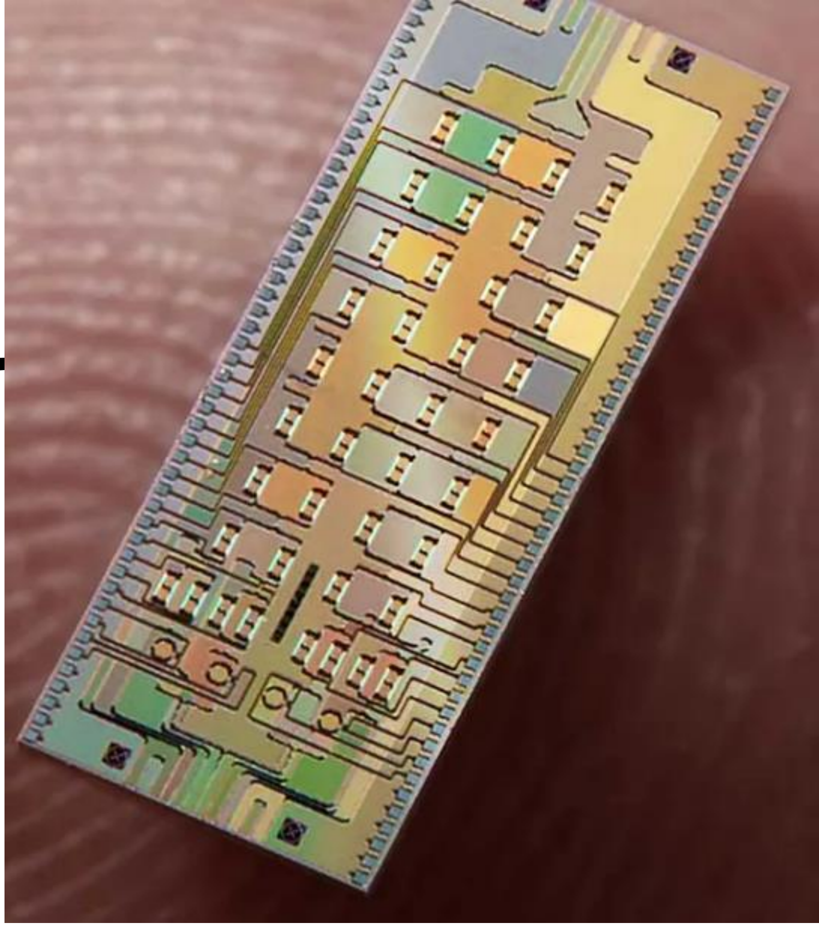
6

Quantum Diamond Technologies

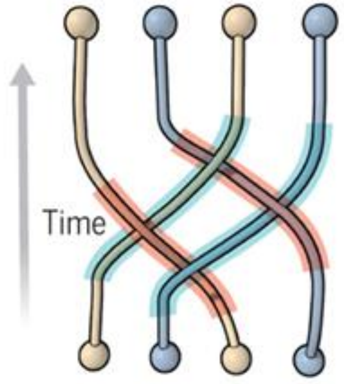
Can operate at room temperature.

Difficult to entangle.

PHOTONIC QUBITS



TOPOLOGICAL QUBITS



Topological qubits

Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.

N/A

N/A

N/A

Microsoft, Bell Labs

Greatly reduce errors.

Existence not yet confirmed.