Quantum: Introduction, Concepts, and Applications

Luis Mendoza, PhD

Fermilab

What is quantum?

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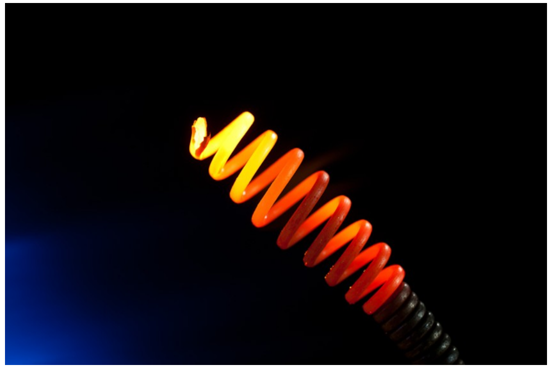
Black-body radiation



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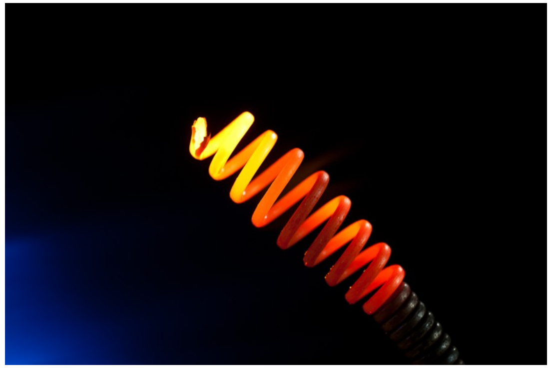
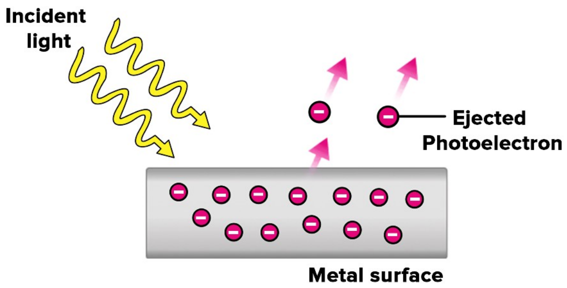


Photoelectric Effect



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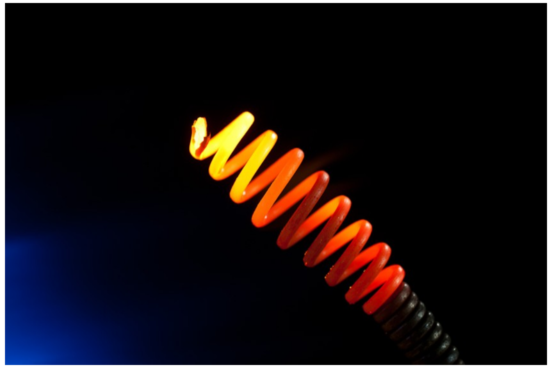

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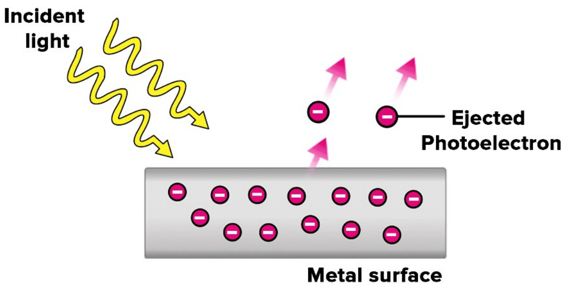
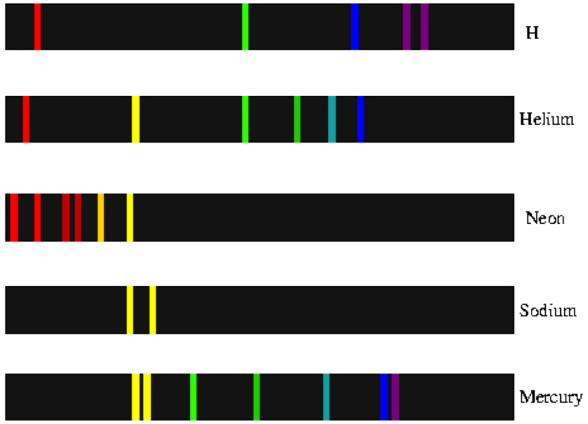


Atomic Spectra

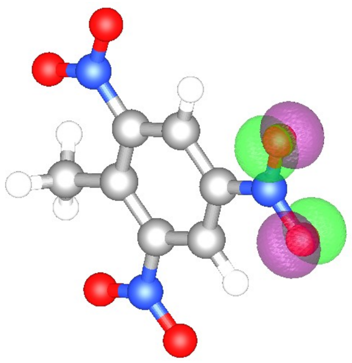


And many more…

What is quantum?

- Very different from classical physics!
- Counter-intuitive but also very useful!
- Has impacted several fields:

Chemistry



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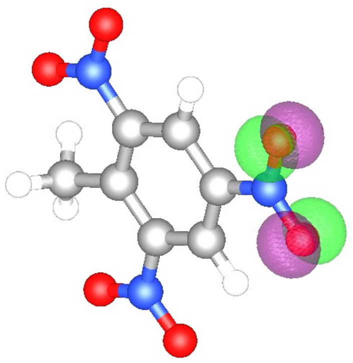

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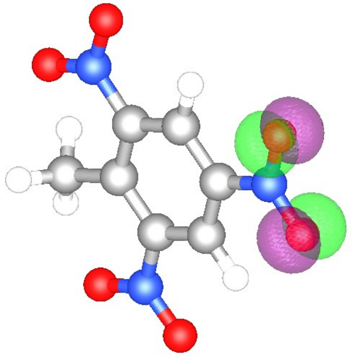

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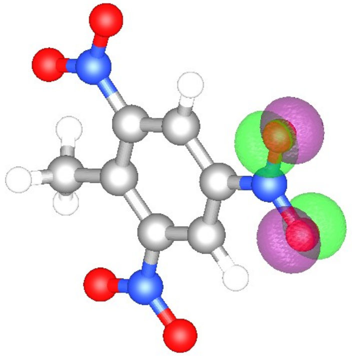

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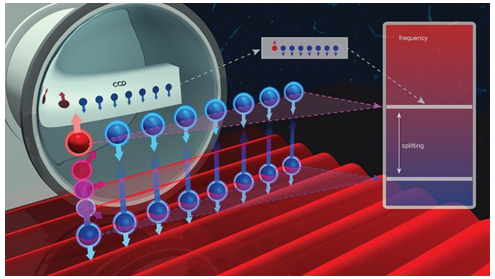

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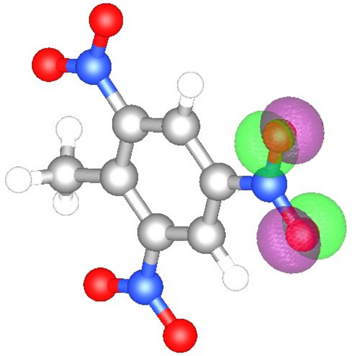

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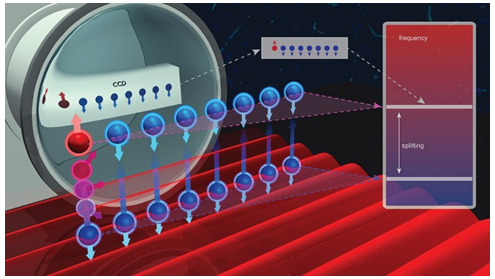
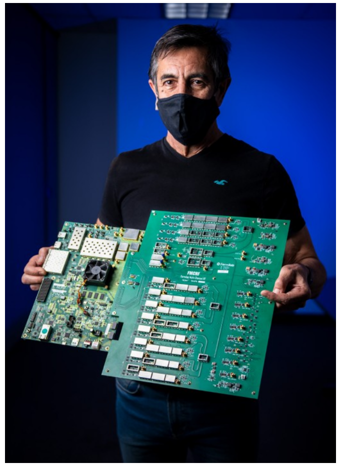
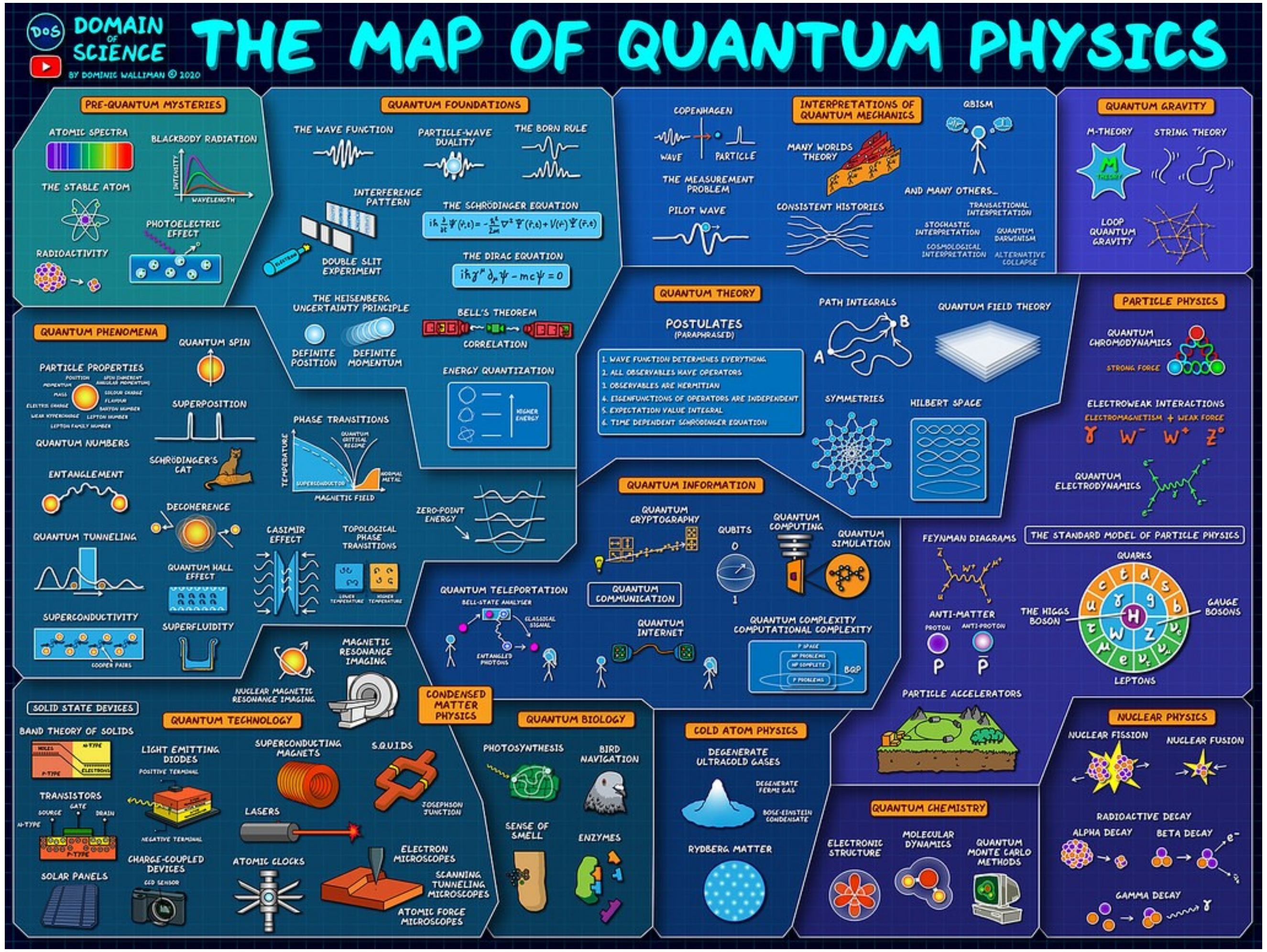


Engineering



Important Concepts

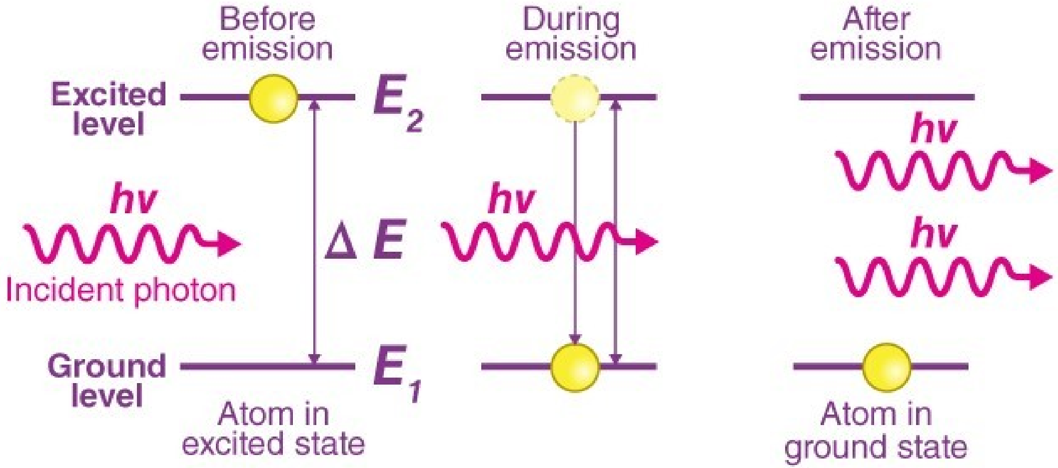
- Quantum is a vast, deep field with new applications and ideas being worked on every day
- Can’t possibly cover everything but we can cover some of the more important concepts
    - Particle-Wave Duality
    - Superposition
    - Entanglement



Particle-Wave Duality

- At the quantum level particles (like electrons) can behave as waves, and waves (like light) can behave as particles

Light as particles



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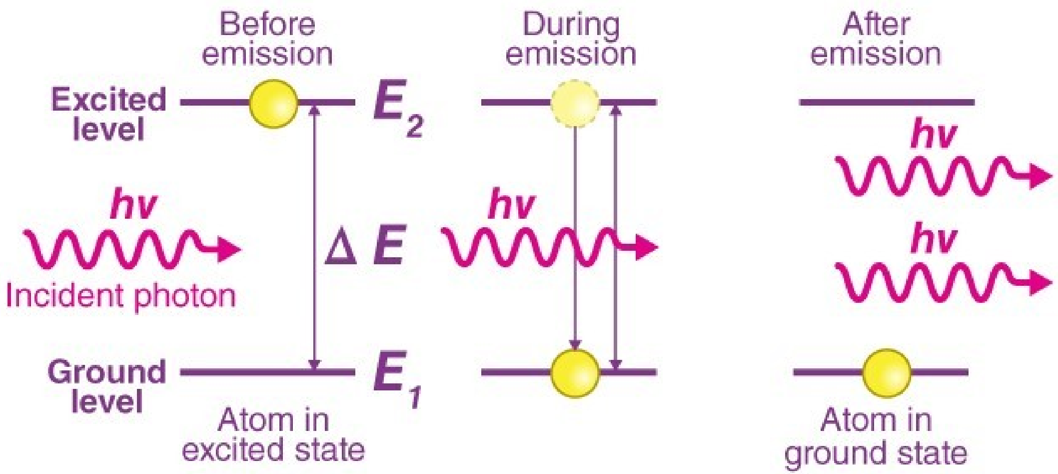

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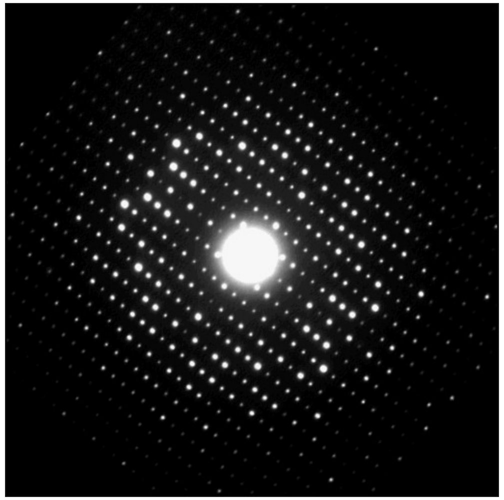
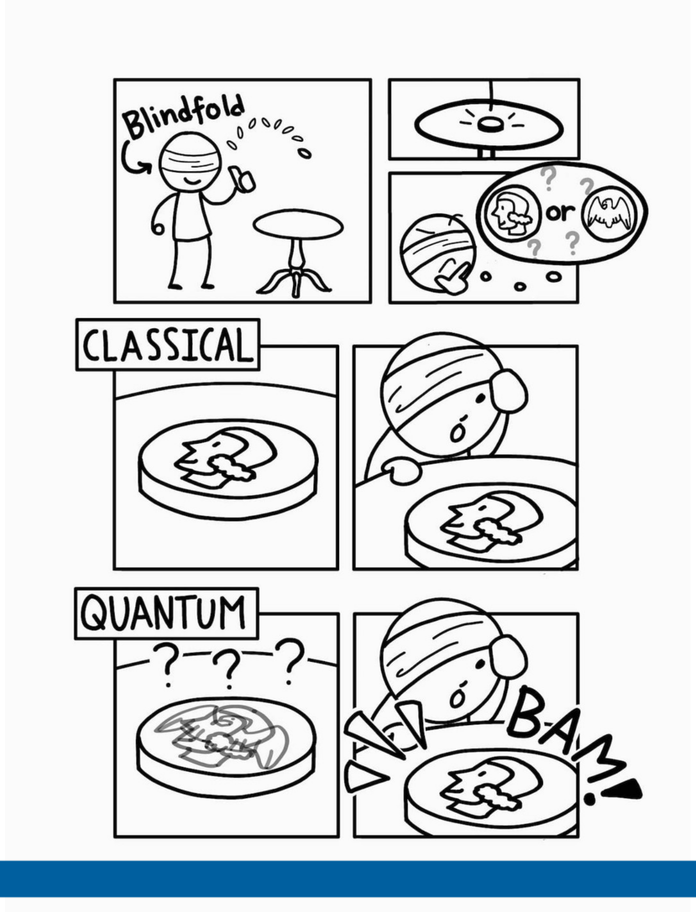


Electron diffraction

Superposition

- Most quantum systems live in a superposition of many states



Directly observing the system has many different outcomes

Direct observations don't have a definite result,
only different results with different probabilities

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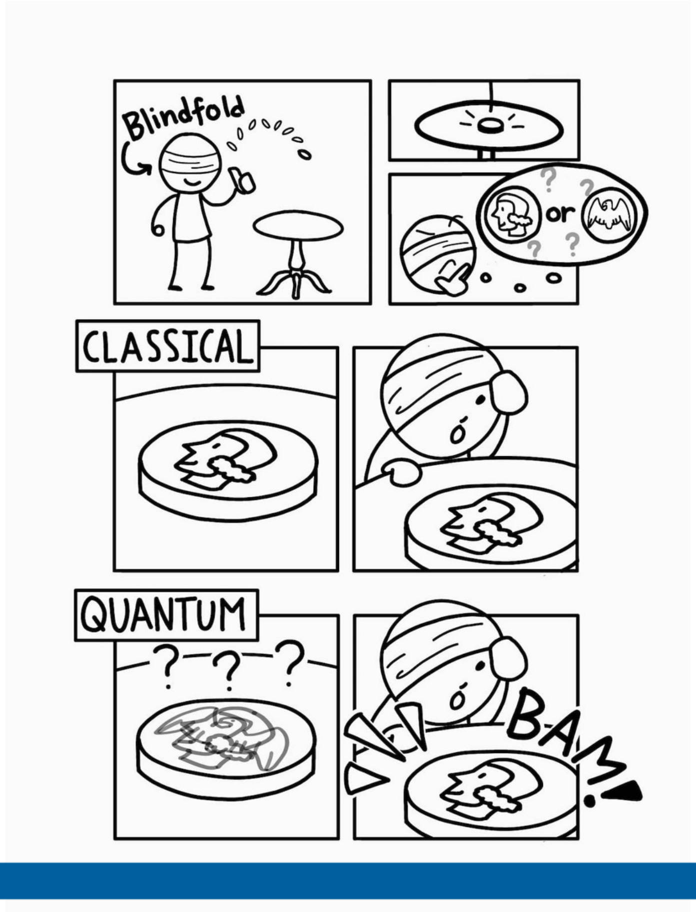

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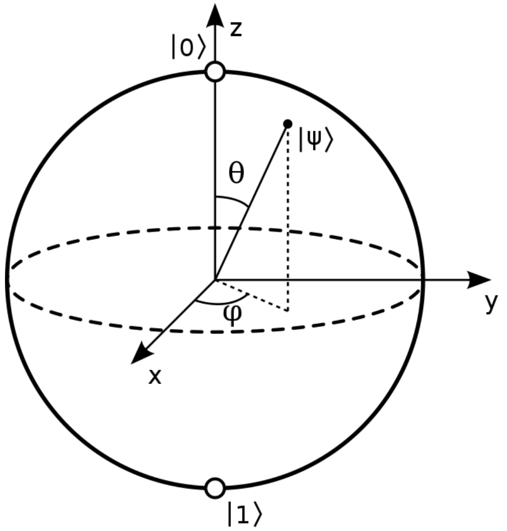
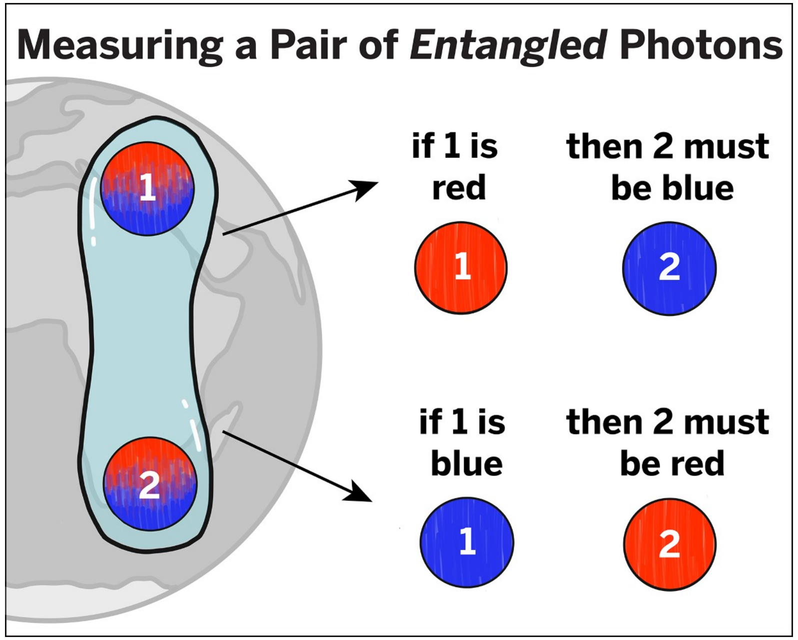
Scientists use the Bloch sphere to visualize these superpositions



Entanglement

- Sometimes, quantum particles can become connected in a certain way and start behaving as a single system. This is known as entanglement



Entangled particles know each other's state no matter how separated they are

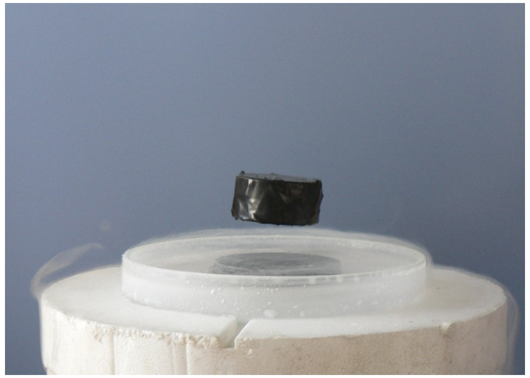
If you observe a certain property of one particle, then you will know exactly the value of that property for the second particle

Quantum Materials

- Quantum effects only appear at subatomic sizes, but in certain situations they can have macroscopic effects!

Quantum Materials

Superconductors



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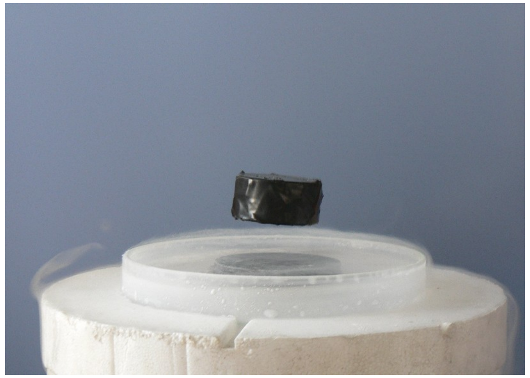
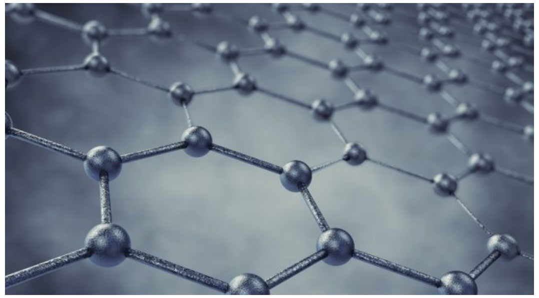


Graphene



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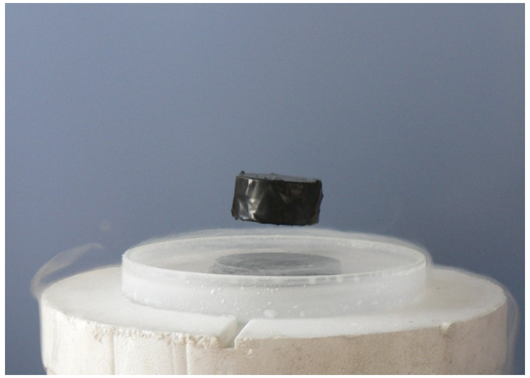

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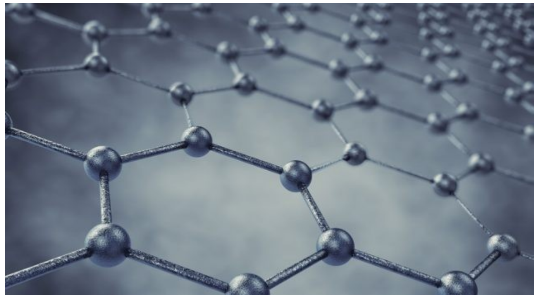
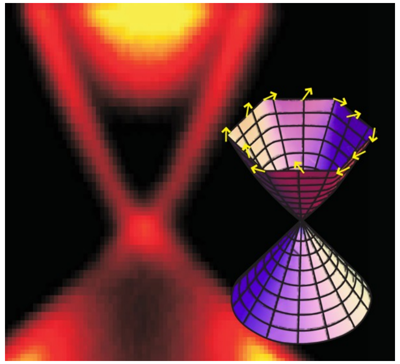


Topological Insulators



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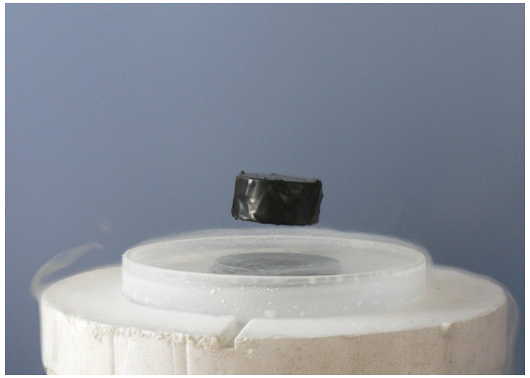

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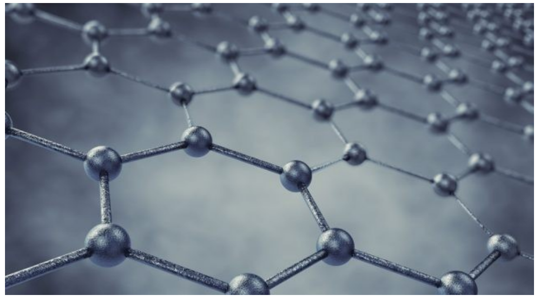

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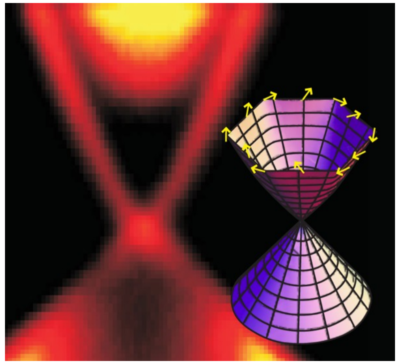
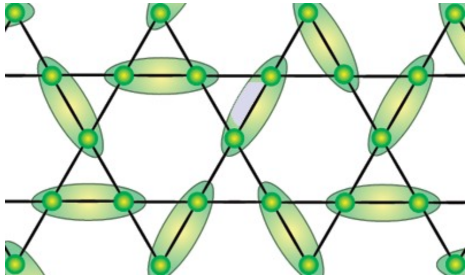
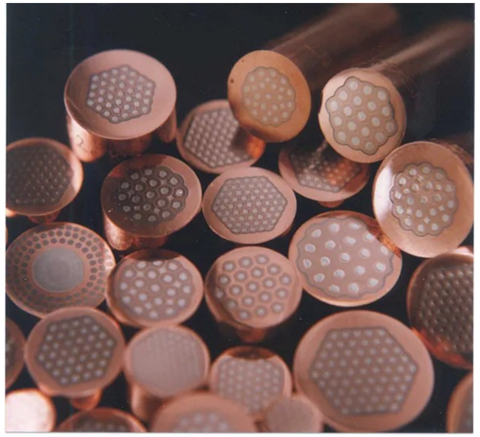


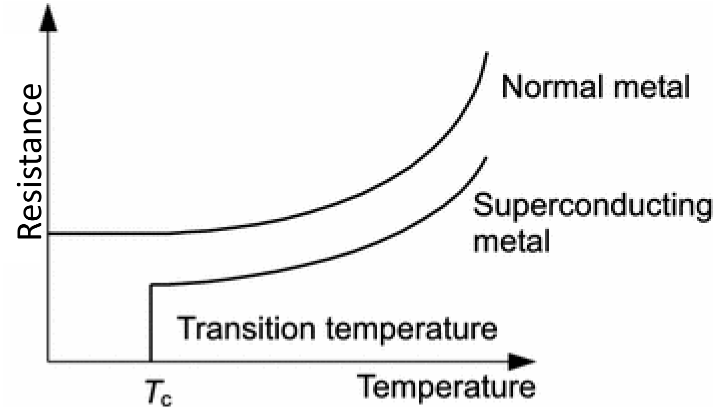
Spin Liquids

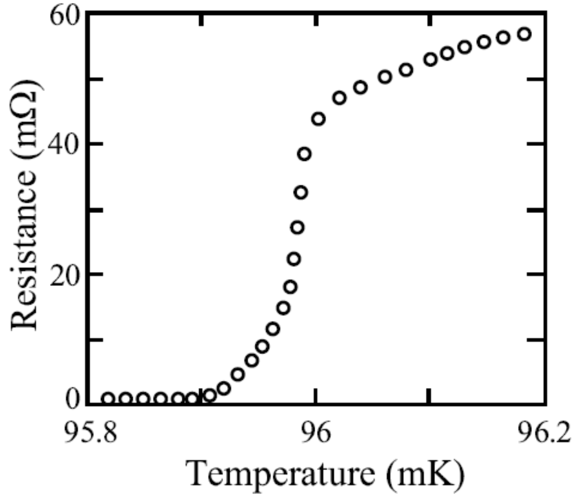


Superconductors

- Certain metals, alloys, and ceramics can conduct electricity with zero electrical resistance when cooled below a certain critical temperature.





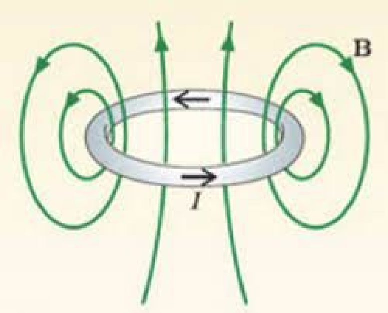


- First material discovered to be superconducting was mercury, tin, and lead in 1911 by Kamerlingh Onnes.

Superconductors

- This behavior can only be explained using quantum physics!

- Electric currents can flow in superconductors without an external voltage



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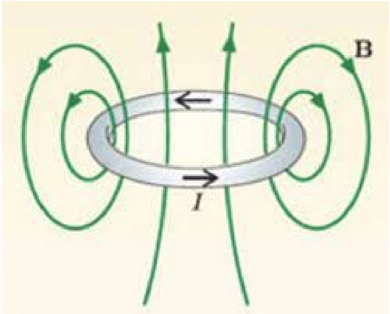
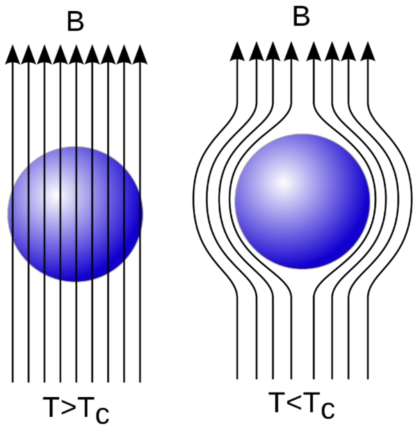


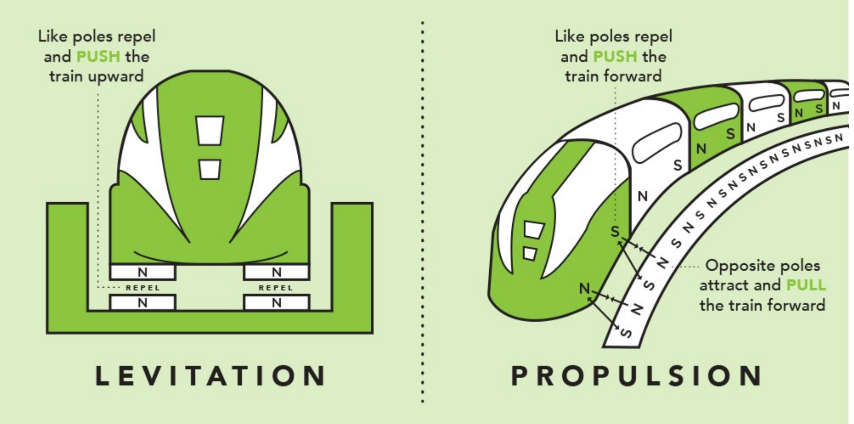
- Superconductors expel magnetic fields (Meissner effect)



Superconductors: Applications

- Very strong superconducting electromagnets

Maglev trains



MRI machines

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- Very strong superconducting electromagnets
- Superconducting electric generators and power lines

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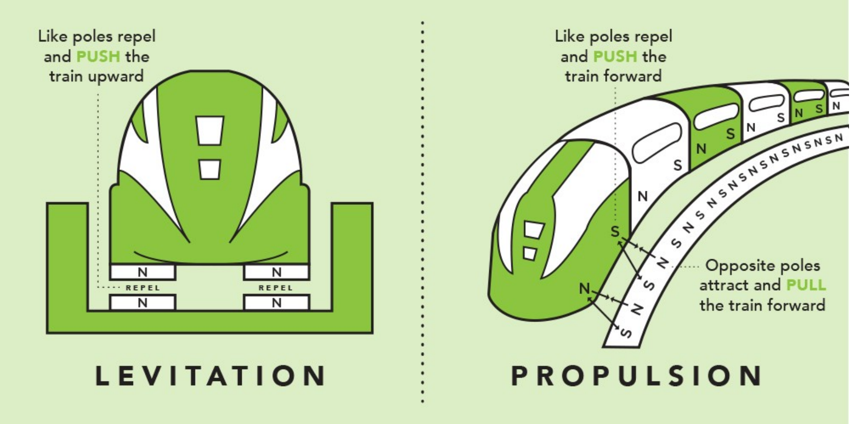

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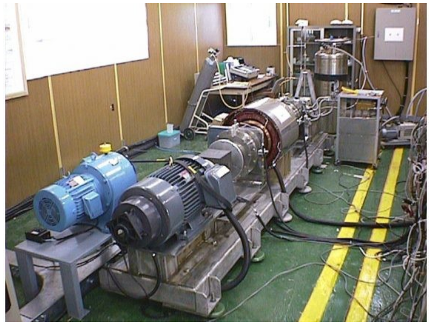

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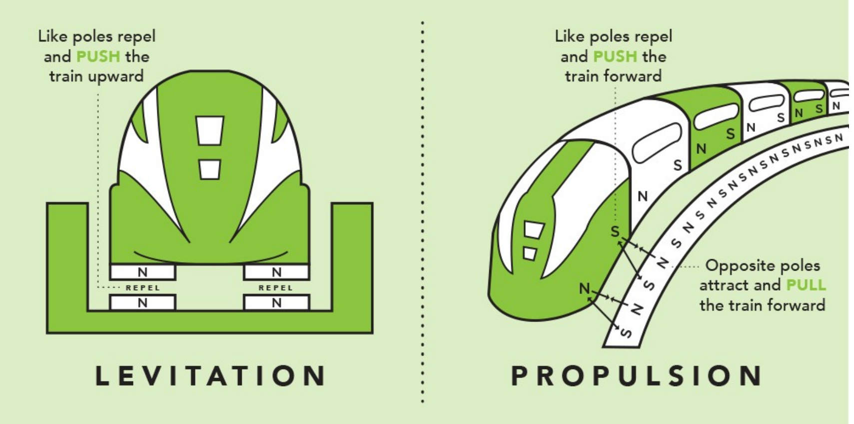

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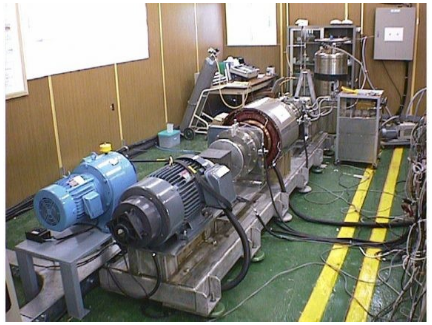
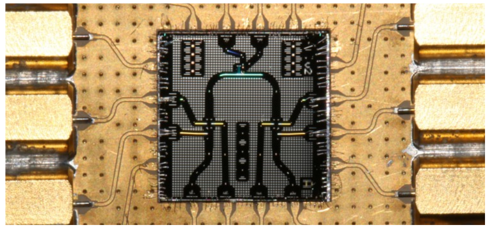


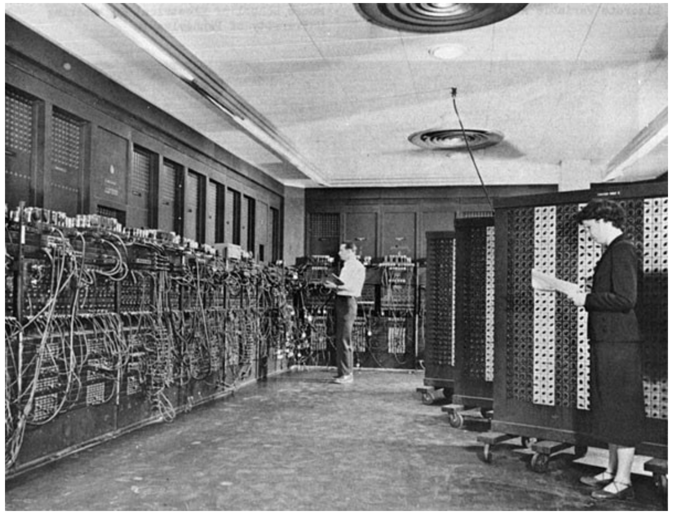
- Superconducting circuits for quantum computing



- And many more!

Quantum Computers, Why? (Reason 1)

Classical computers have become much smaller as time goes on



1940s

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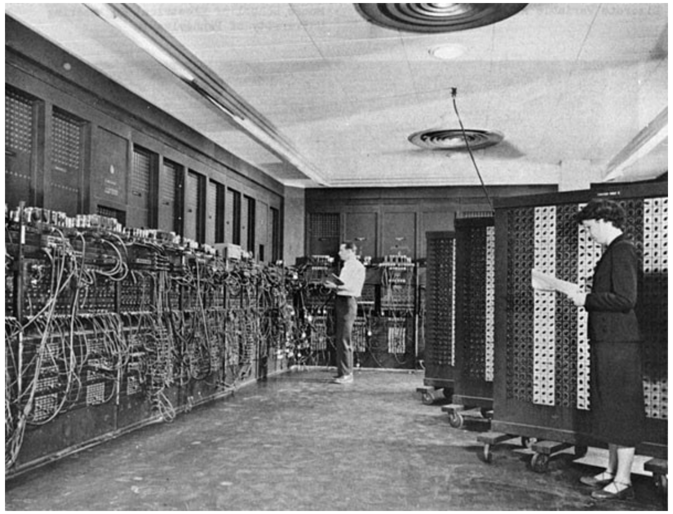


1940s

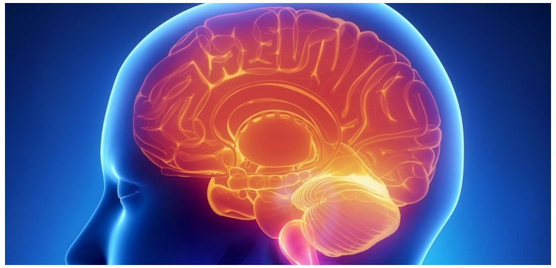
2020s

How did classical computers become so small?

Quantum Computers, Why? (Reason 1)

Microprocessor

Brain of the computer



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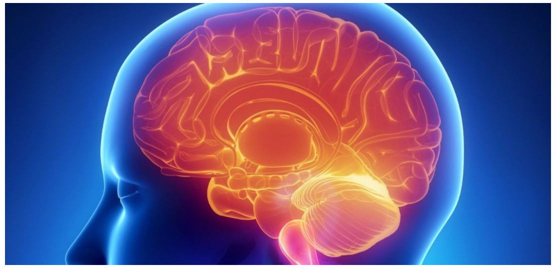

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Putting in more transistors makes your computer faster!

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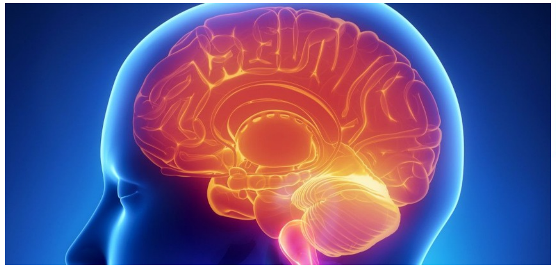

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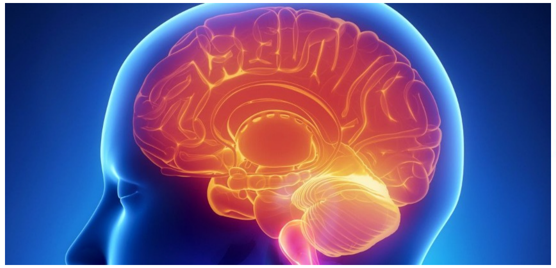

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For very small objects the laws of physics become governed by quantum physics

A computer based on quantum physics would avoid this problem entirely!

Quantum Computers, Why? (Reason 2)

Nowadays a lot of our personal information is online

amazon Online shopping

Online banking

BANK OF AMERICA

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Requires credit card information

How do we protect this information?

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How do we protect this information? → Encryption!

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Encryption works because factorization is *<u>very</u>* hard for big numbers (for classical computers)

Quantum Computers, Why? (Reason 2)

What is factorization?

Any whole number is either *prime* or a *product of primes*

Primes: 2,3,5,7,11,13,17,19,…

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8994874648911116353 =

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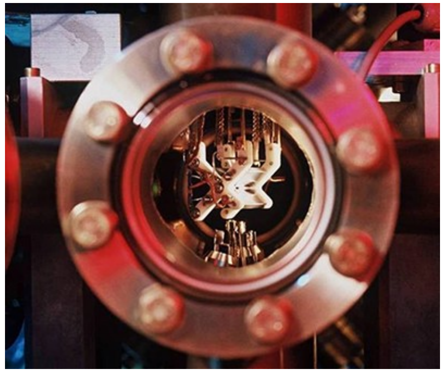
Quantum Computers, Why? (Reason 2)

Quantum computers are <u>*much*</u> more efficient at factorizing big numbers (Shor's algorithm)



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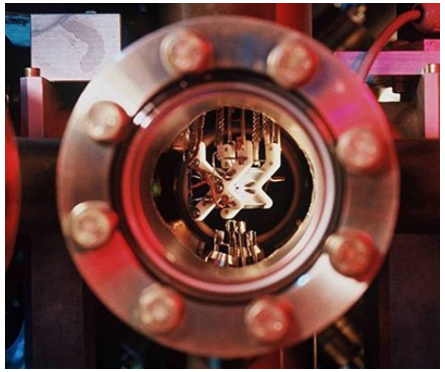
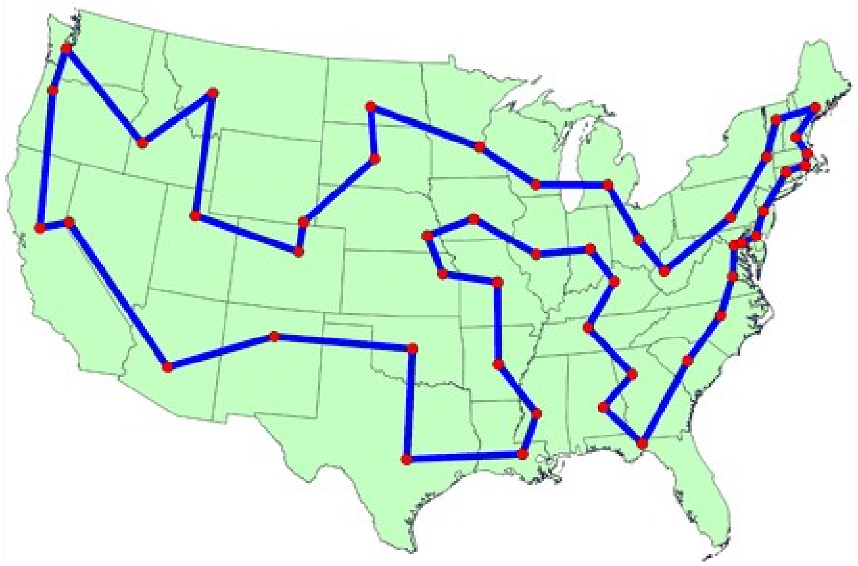


Quantum computers break classical encryption

This can lead to new, more secure, quantum-based encryption methods

Quantum Computers, Why? (Reason 3)

- Traveling Salesman Problem: given a list of cities, you want to make a round trip that visits each city only once, what is the shortest route?



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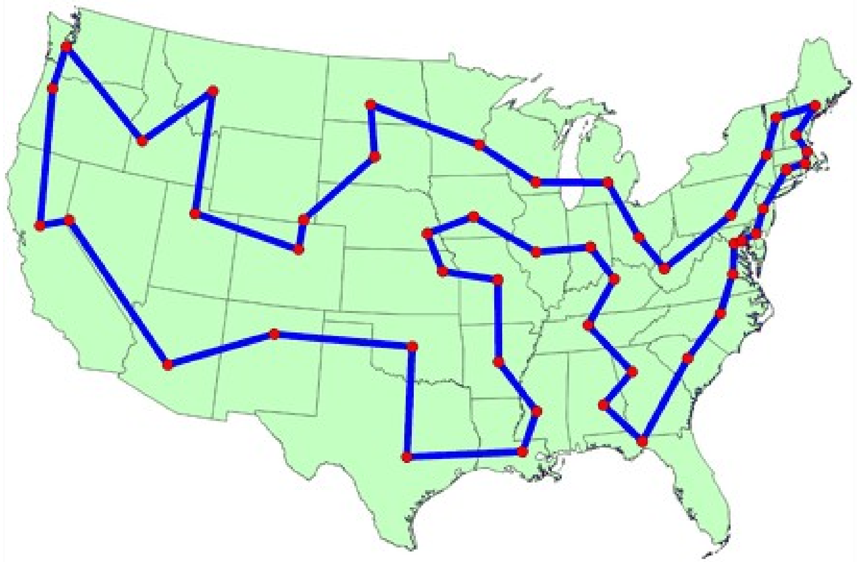

Solving this problem has several applications:

-Supply chain logistics
-Commercial flight scheduling
-DNA sequencing
-Designing telecommunication networks
-Etc…

Quantum Computers, Why? (Reason 3)

- A simple way to tackle this problem is to draw all the possible paths, compare them, and then pick the shortest one

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# of cities	# of paths
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3	6
4	24
5	120
6	720
7	5040
8	40320
9	362880
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We need something more than standard computer to try solving this problem!

Break Time!

Take some time to process everything we have seen so far

Welcome Back!

So far we have seen:

- Particle-Wave Duality

-Superposition

-Entanglement

-Superconductors

-Some limitations of classical computers

  -Factorization

  -Traveling Salesman Problem

Enter Quantum Computers

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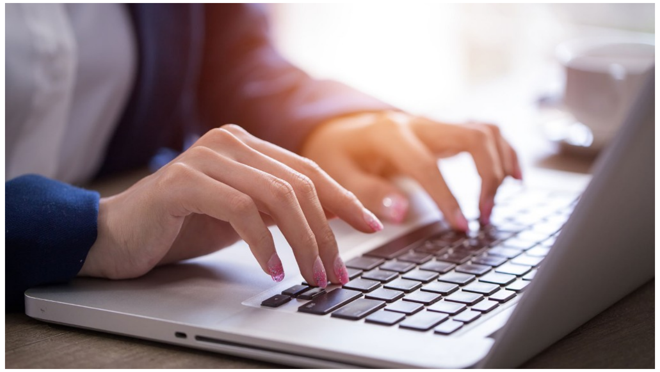
- Classical computers function using bits
- A bit can only be either 0 or 1
- All the data in a classical computer is stored in 0's and 1's, this is called *binary*


What we see

What the computer sees

Enter Quantum Computers

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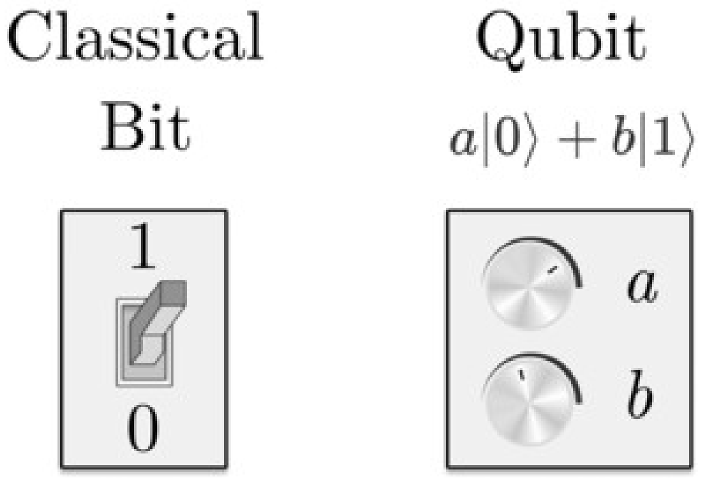
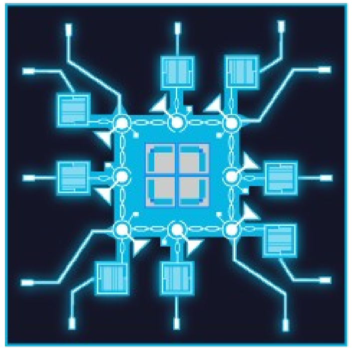


- Qubits can store much more information

Qubits

- There are many different types of qubit

Superconducting Qubits



- Fermilab research focuses on superconducting qubits!

Qubits

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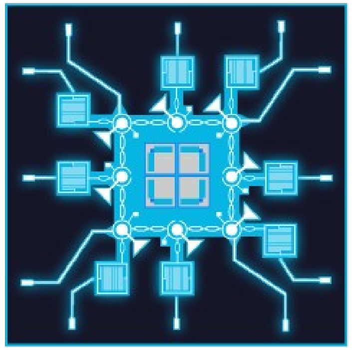
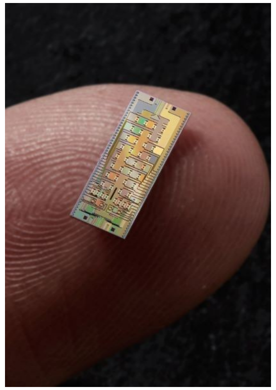
Superconducting Qubits



Photonic Qubits



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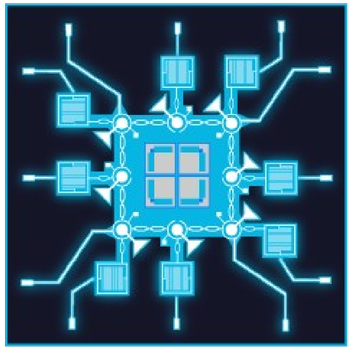

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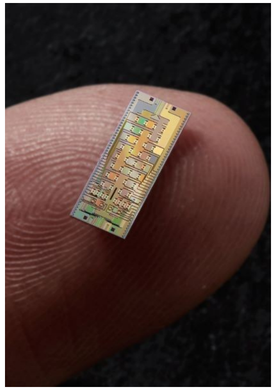
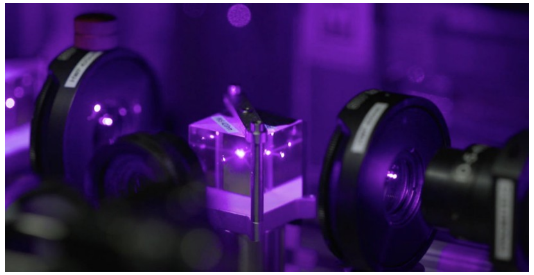


Rydberg Atom Qubits



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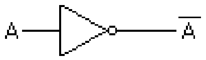
Logic Circuits

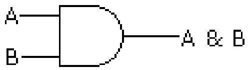
- How do computers process information?

Logic Circuits

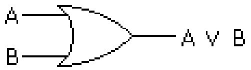
- How do computers process information?
- Logic gates are the basic building blocks of classical computers



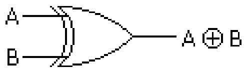
A	NOT A
0	1
1	0



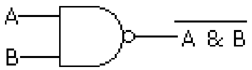
A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1



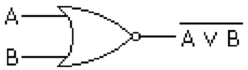
A	B	A OR B
0	0	0
0	1	1
1	0	1
1	1	1



A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0



A	B	A NAND B
0	0	1
0	1	1
1	0	1
1	1	0



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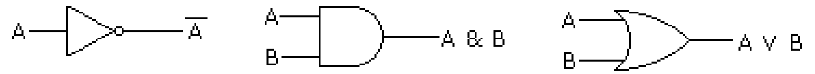

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1	0

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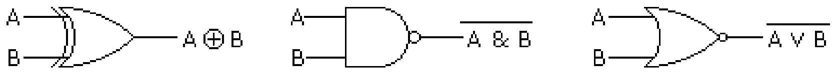

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0	1	0
1	0	0
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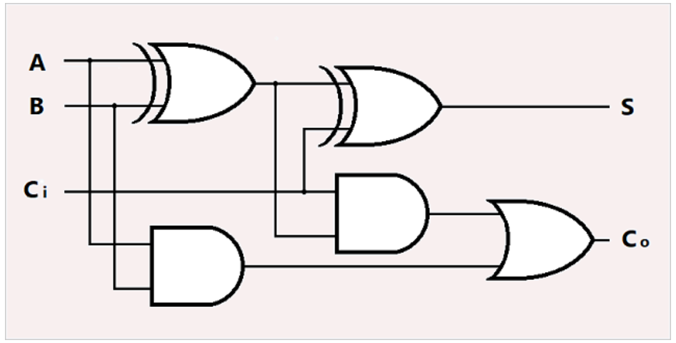
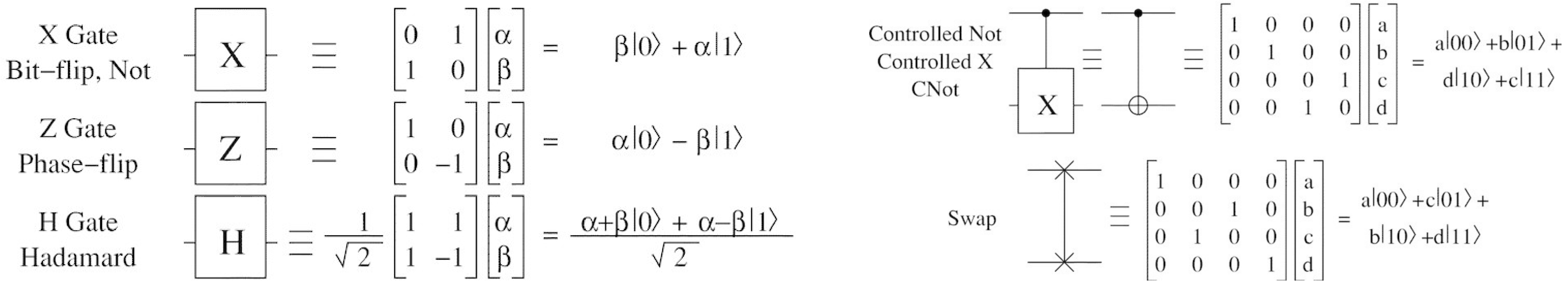
Connecting many logic gates together makes a logic circuit



A standard CPU contains millions of logic gates

Quantum Circuits

- Quantum gates are the basic building blocks of quantum computers



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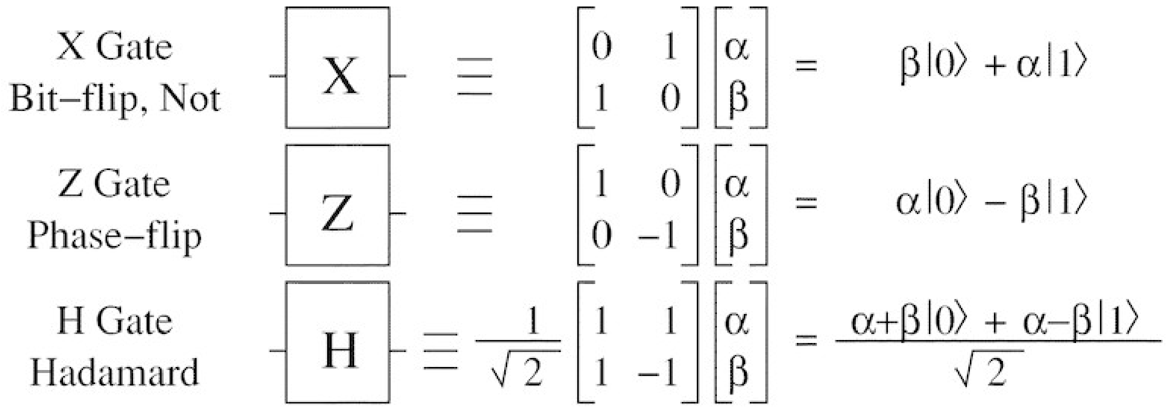
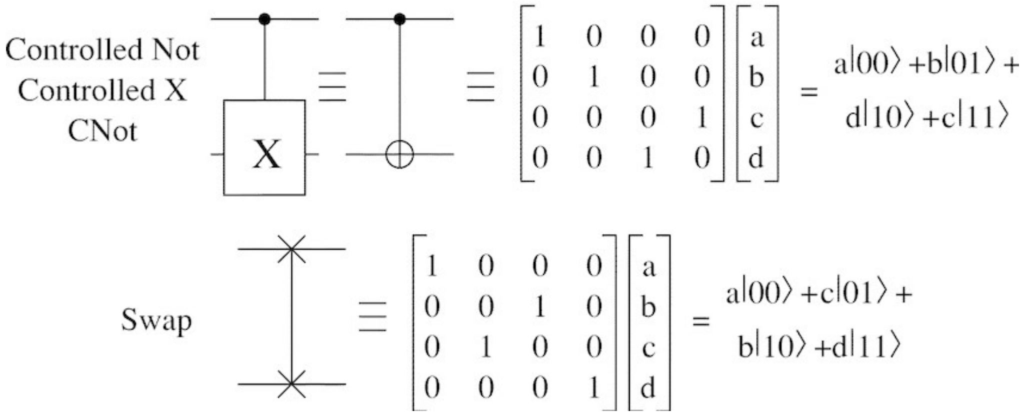
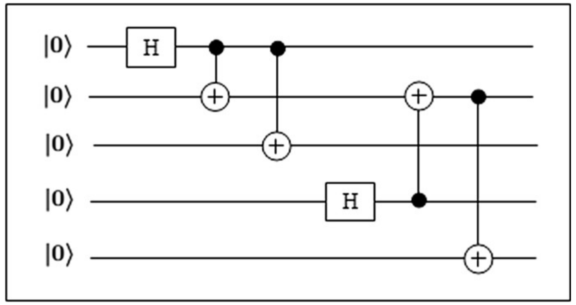




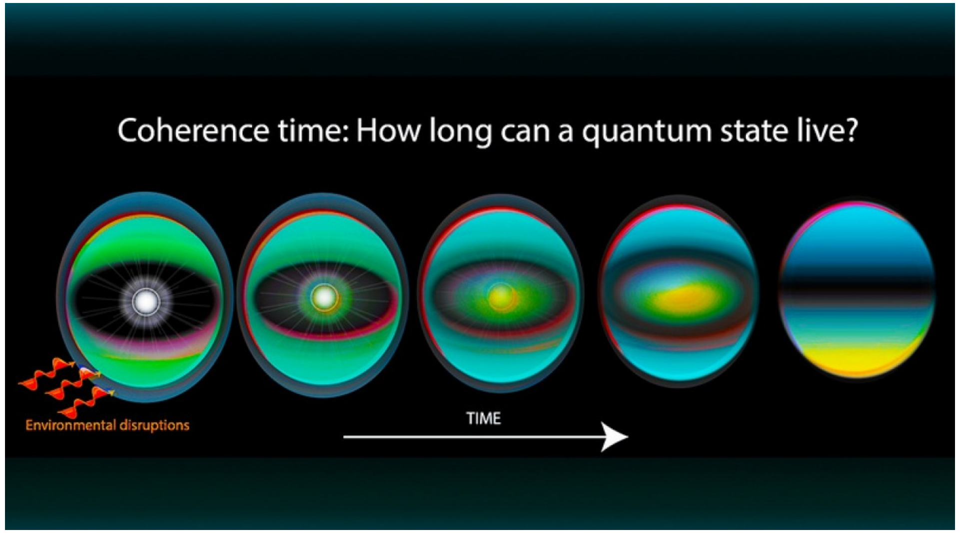
- Quantum gates act on a qubit of the form $\alpha|0\rangle + \beta|1\rangle$



Putting many quantum gates together creates a quantum circuit

Obstacles

- Qubits are very sensitive to external disruptions and really difficult to handle. This is called decoherence.



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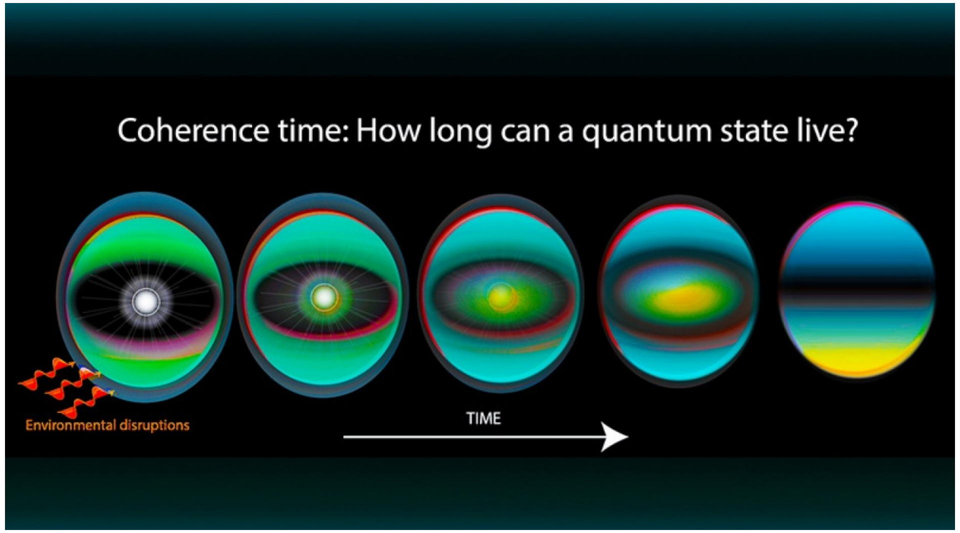

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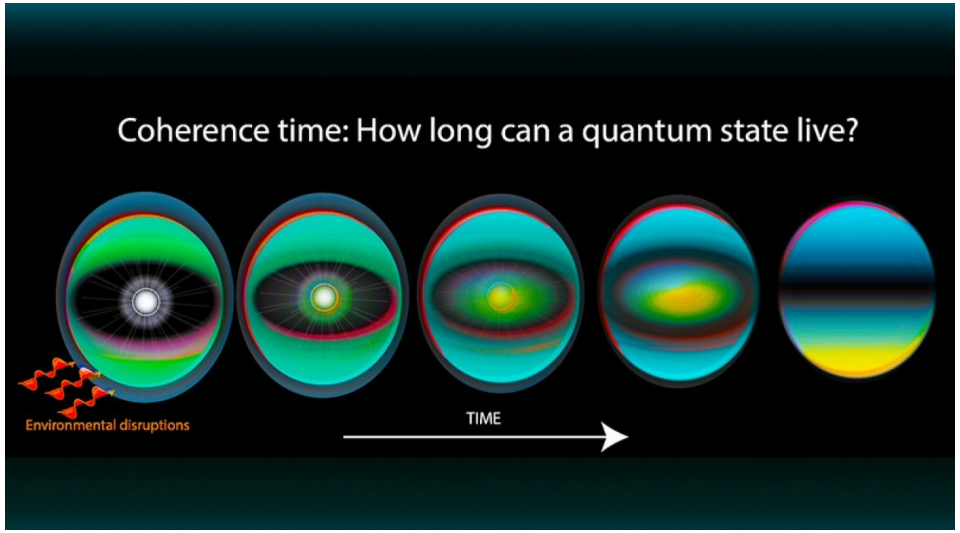
- Scaling (can only control a few qubits at a time)



Quantum Sensors

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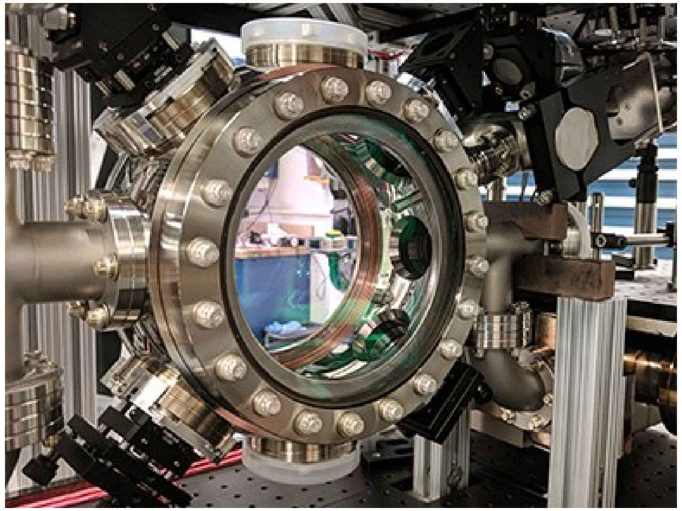

MAGIS-100 (Fermilab)

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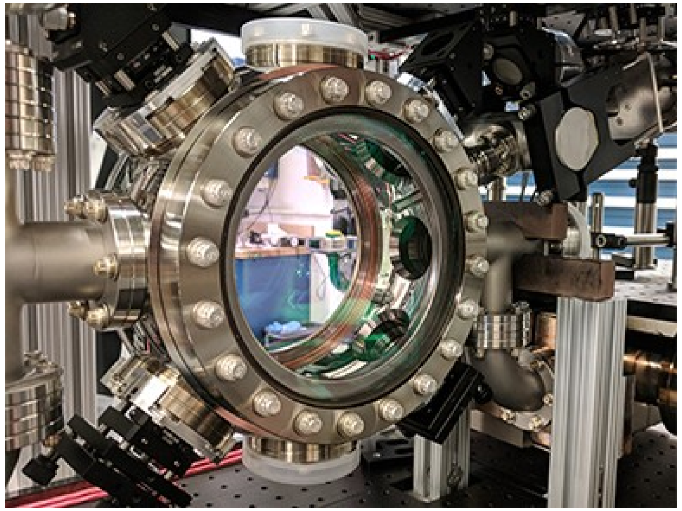

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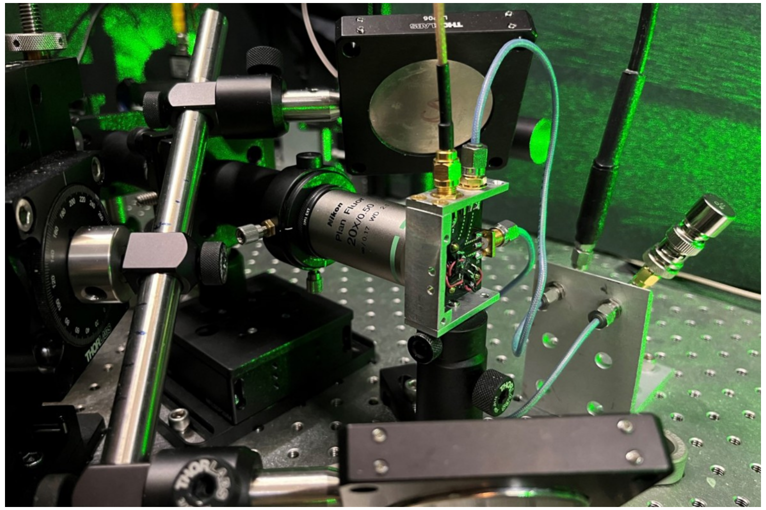
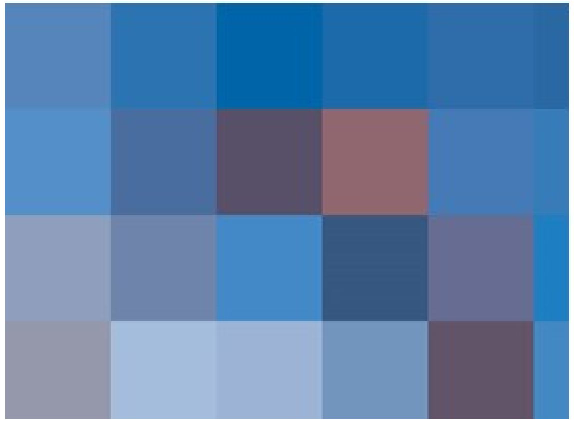


Quantum Sensor (MIT)

Quantum Sensors

- What do we want high precision for?



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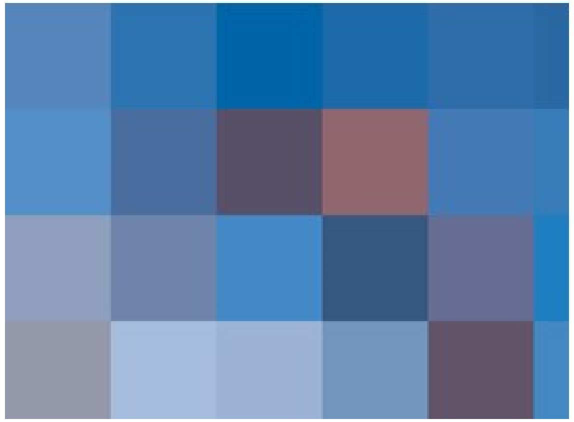

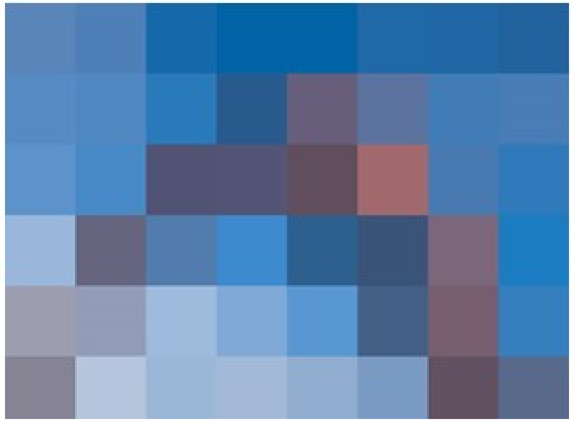

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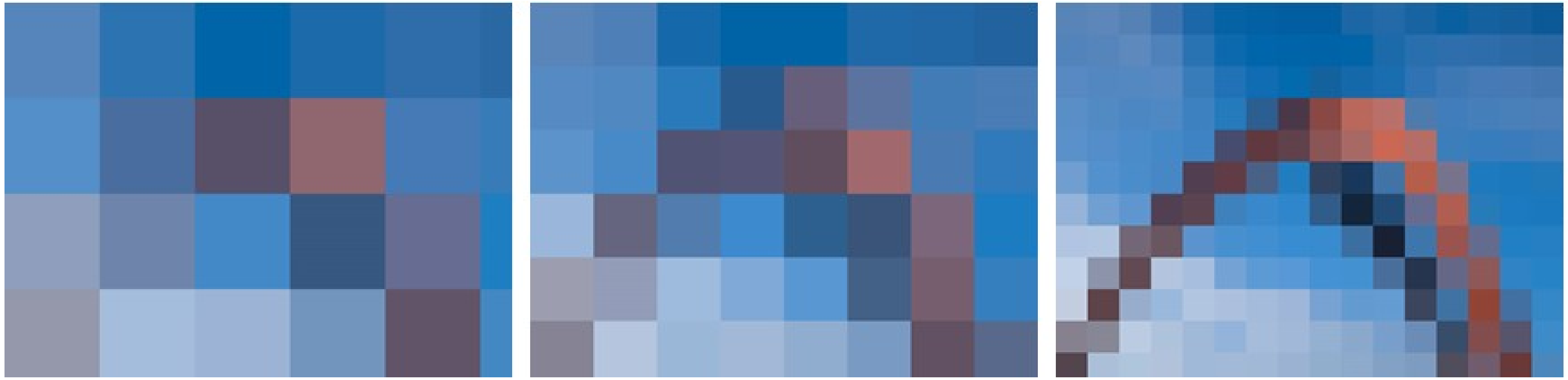

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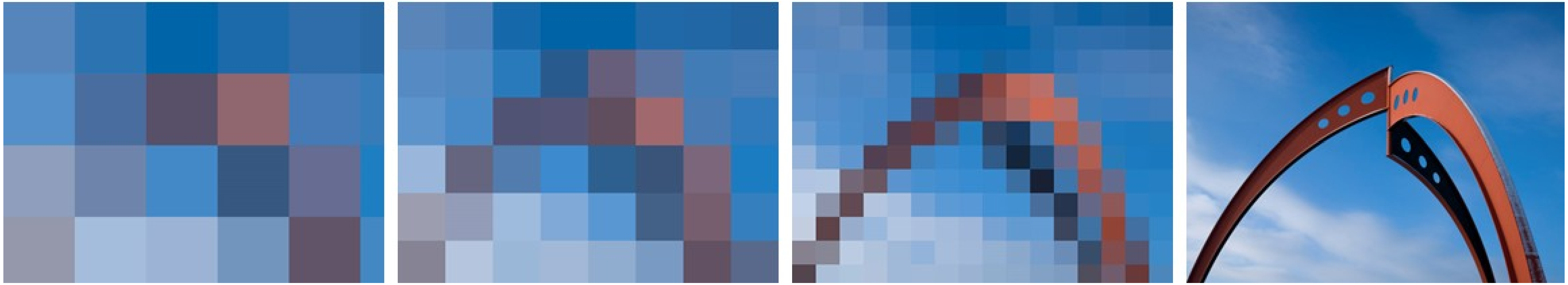

- As precision increases new features are discovered.

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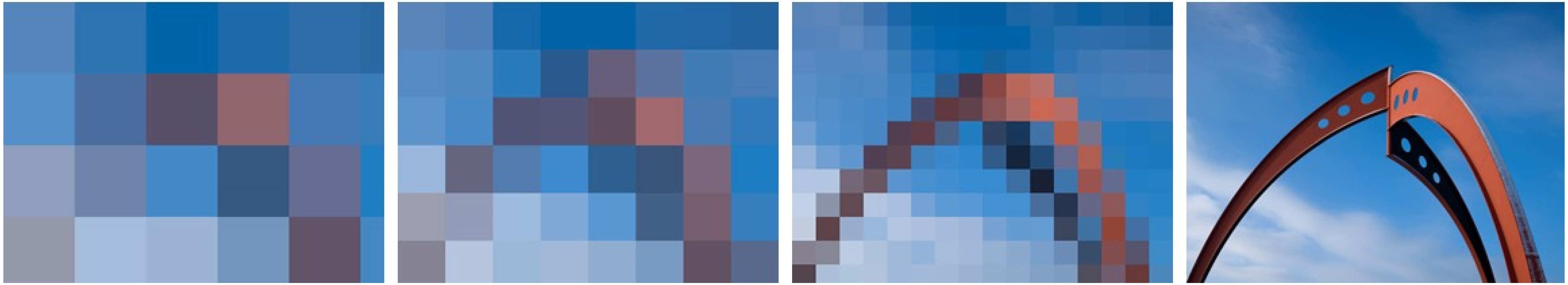

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- Chemistry example: sodium doublet.

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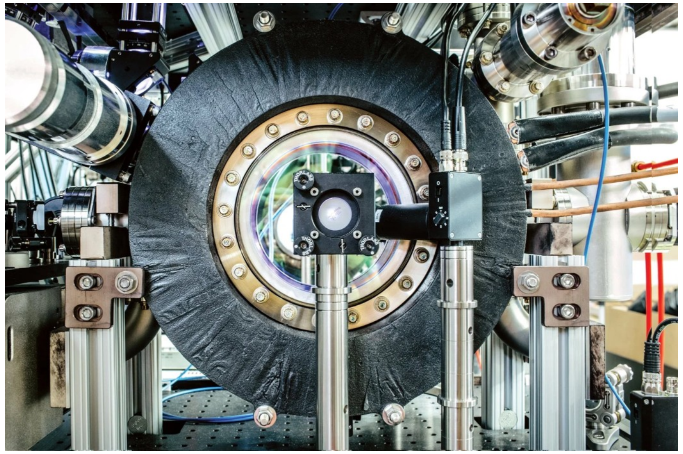
Gravitational
wave detection



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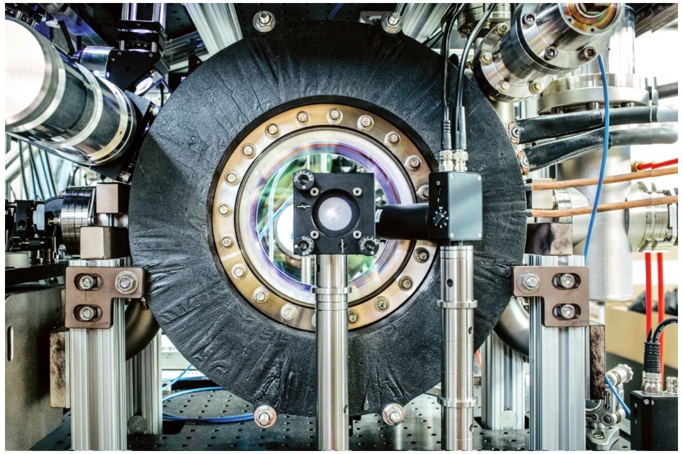

Dark matter detection

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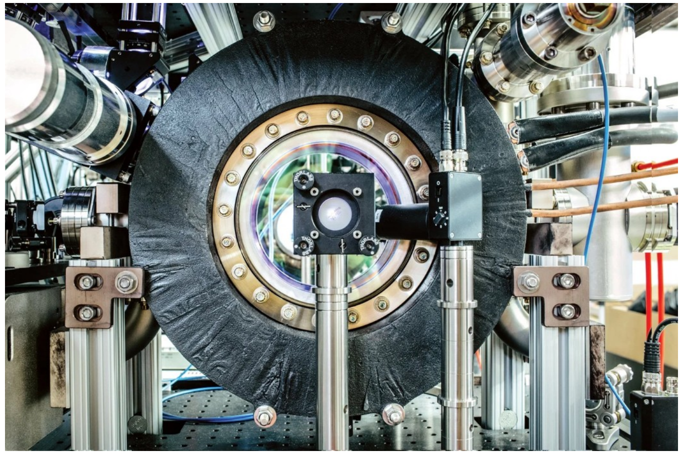

Dark matter detection

Medical imaging