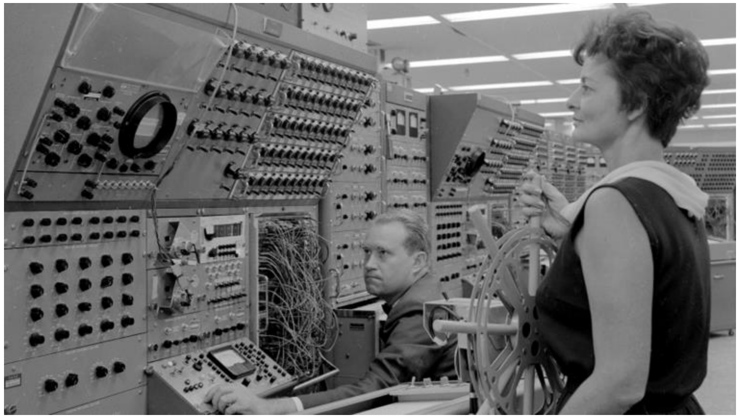
Thanks Prof Alex Ma!

I "borrowed" several slides from Prof Alex Ma PHYS 342 course: AM

Classical computers

Analog
(inputs/outputs are continuous variables), e.g. trajectory of missiles

Antikythera
ancient Greek astronomical calculator, 200BC



More powerful till 1950/60s, some even after 1980s

Digital
(inputs/outputs are discrete variables), e.g. accounting / finance

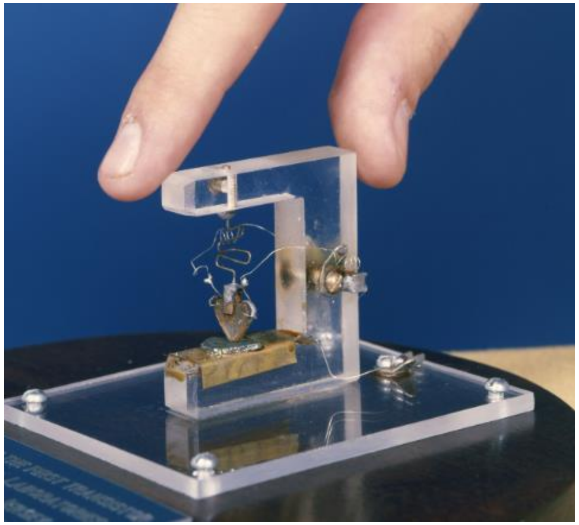
AM

Classical digital computers - 0s & 1s

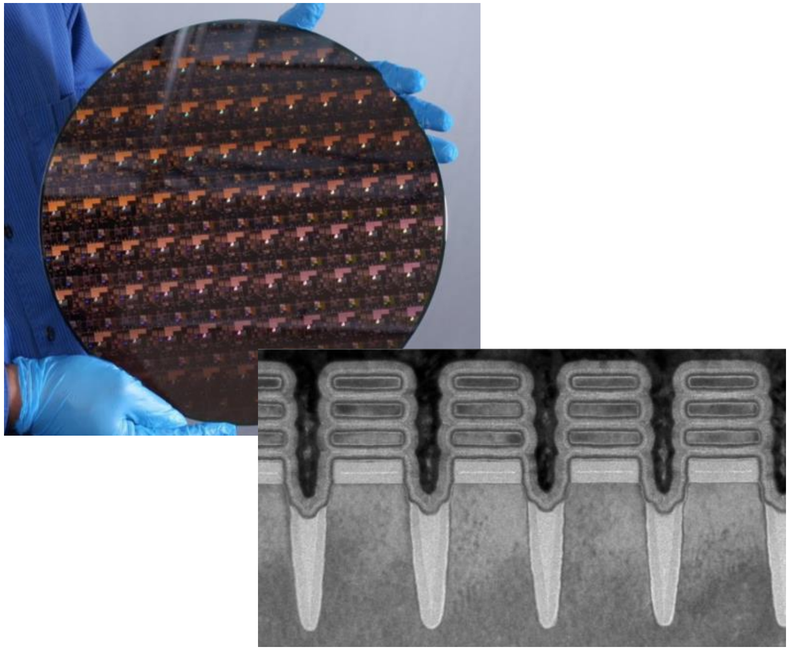
Information as bits

Computing: **Transistors** as switches for electrical currents

e.g. 0 = no current, 1 = has current



First transistor, Bell labs, 1947

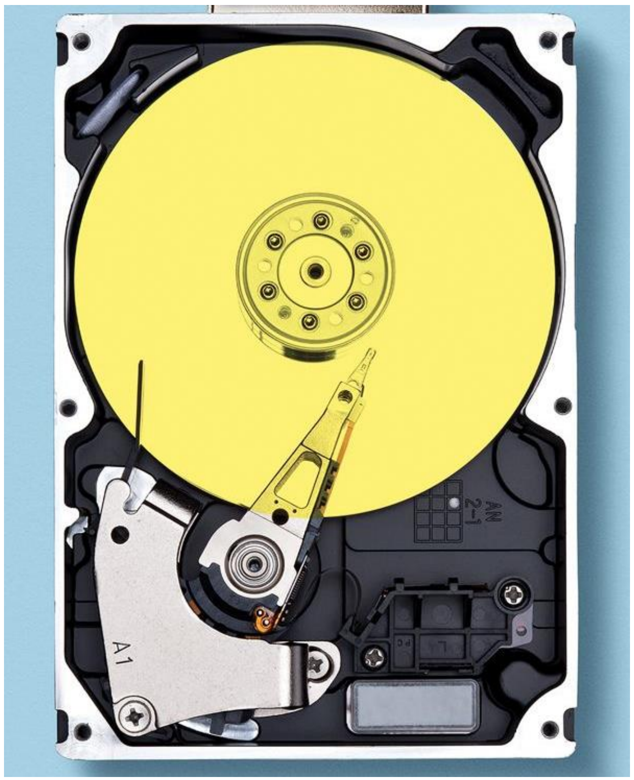


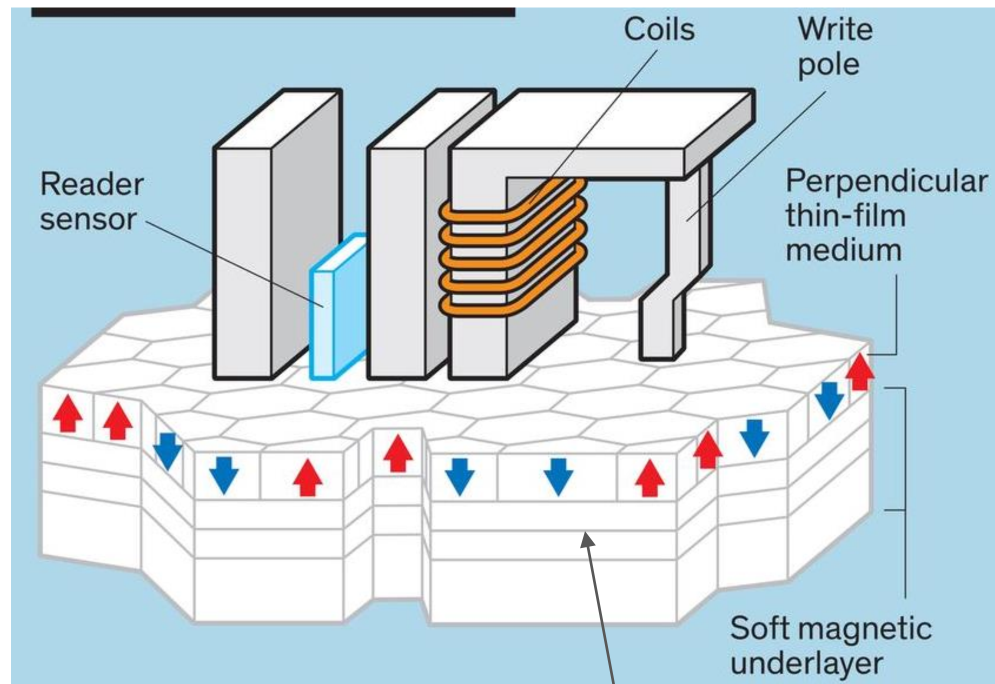
IBM 2-nm transistors, 2021

Classical digital computers - 0s & 1s

Information storage: Hard drive - small magnets

(e.g. North pole up = 0, South pole up = 1)



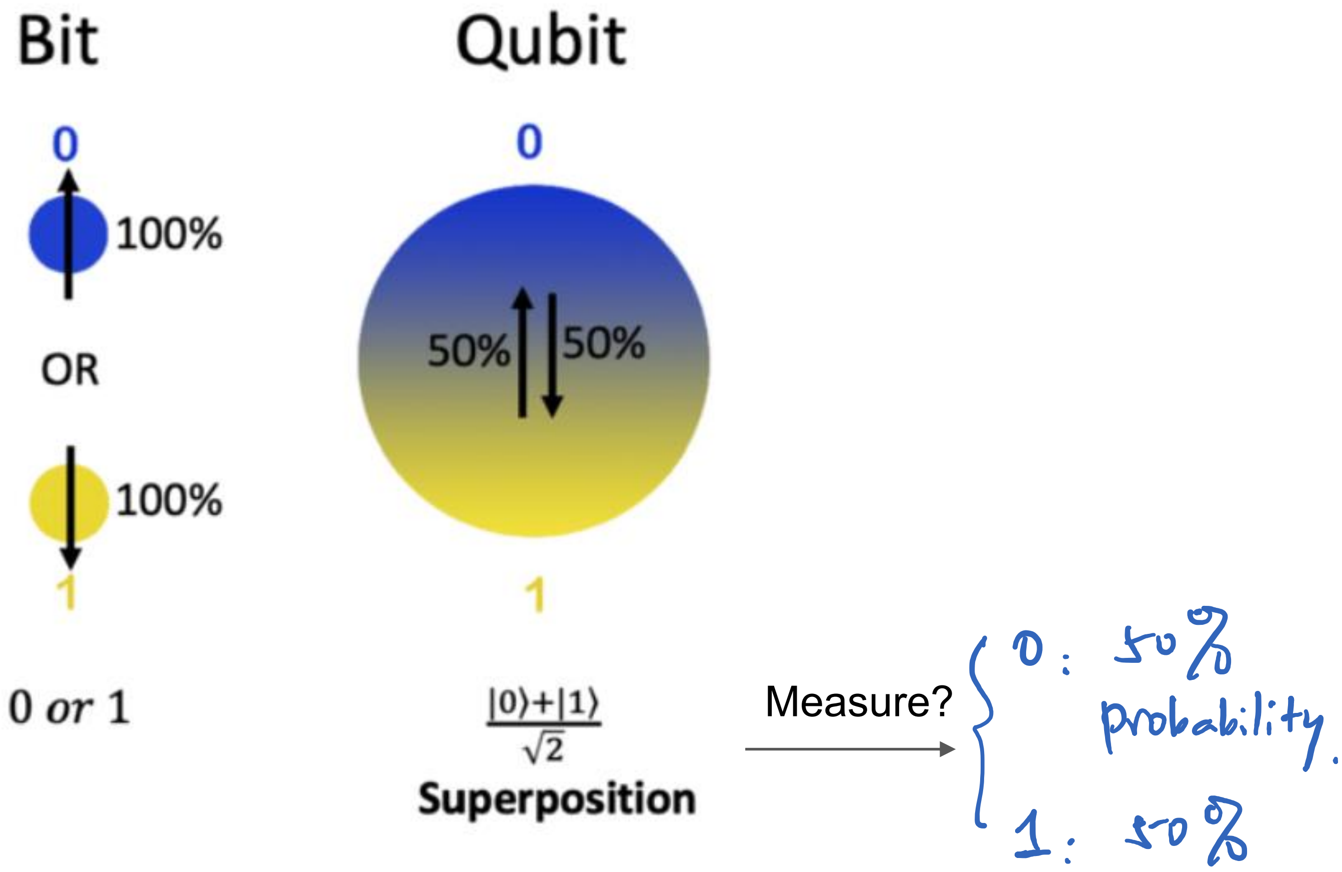


Traditional hard drive

~ 10nm, few ns for read/write

Quantum information - Qubit

- Qubit (Quantum bit) – can be in any superposition of 0 and 1!



Quantum resources

(what will quantum machines be build from?)

Spin from: electron, atom, molecule etc...

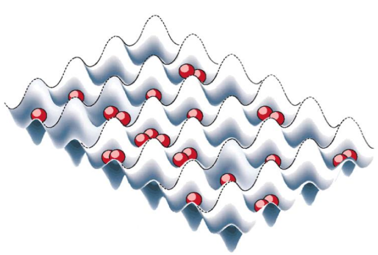
0? 1?

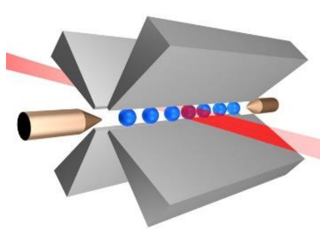
- Spins - $\frac{1}{2}$ $\uparrow, m_s = +\frac{1}{2}$; $\downarrow, m_s = -\frac{1}{2}$.
- Atoms : 1s orbital ; 2s orbital
- Photons : polarization: horizontal ; vertical.
- Quantum dot/well : particle in a box, similar to atom.
- Superconducting circuits 0 = no current ; 1 = has current.

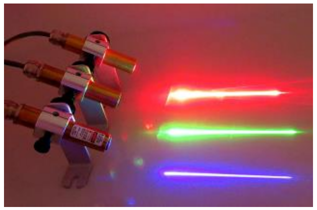
→ quantum electrical circuits.

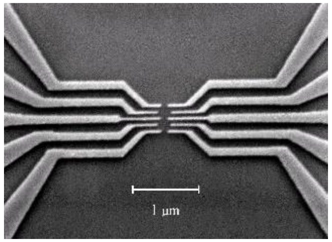
Many physical platforms:

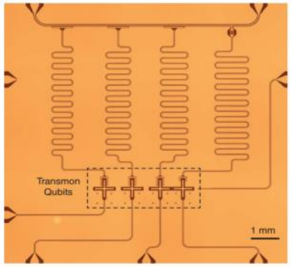
cold atoms, trapped ions, photonics, quantum dots, superconducting circuits











Quantum algorithms and applications

Digital algorithms:

- Deutsch-Jozsa algorithm (1989)
- Shor algorithm (1994) - factoring integers
- Glover algorithm (1996) – search
- Etc…

Applications:

- Optimization,
- Search,
- Encryption..

But most importantly – to calculate the quantum world!

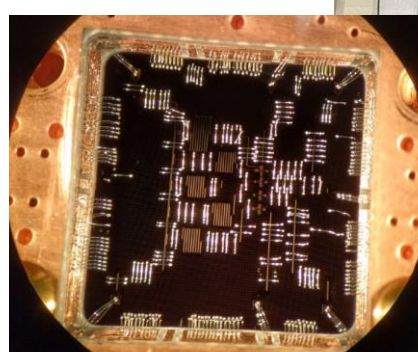
- Quantum chemistry – drug discovery
- Material science – power/energy transfer; data storage
- Biological processes – e.g. photosynthesis
- Explore new physics!

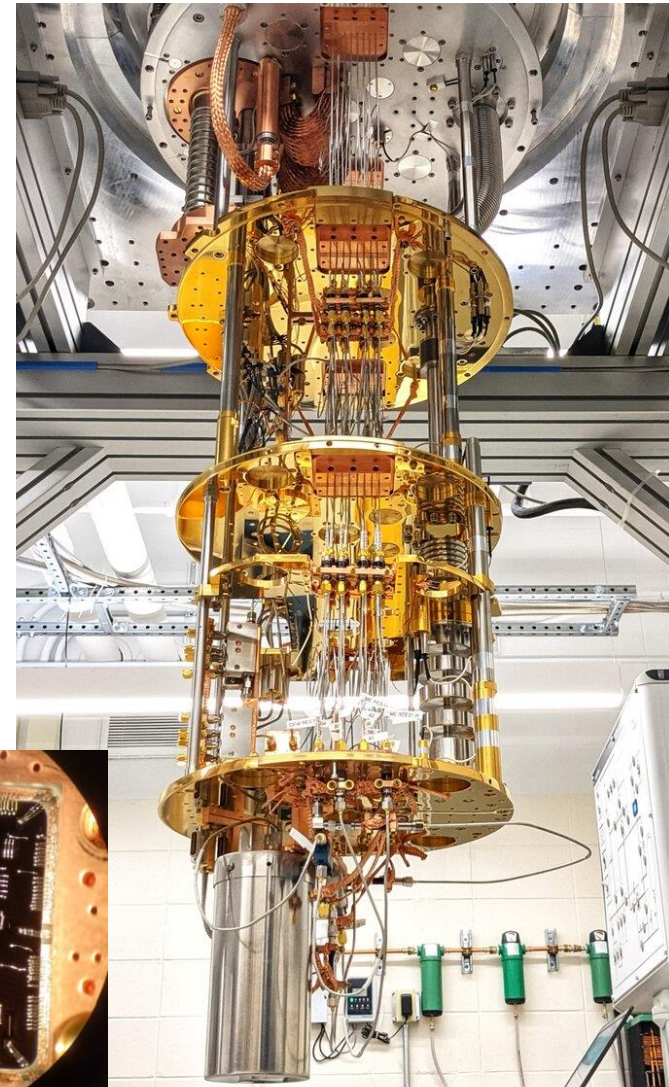
Quantum Simulators ("special purpose quantum computers")

Wait... Don't we already have quantum computers?

- Existing platforms face many challenges
  - Small number of physical qubits
  - No quantum error correction (yet)
- Quantum analogue of silicon has not been identified
  - We are at the beginning of the revolution

"8 bit QPU" …

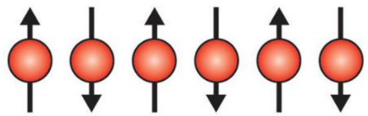




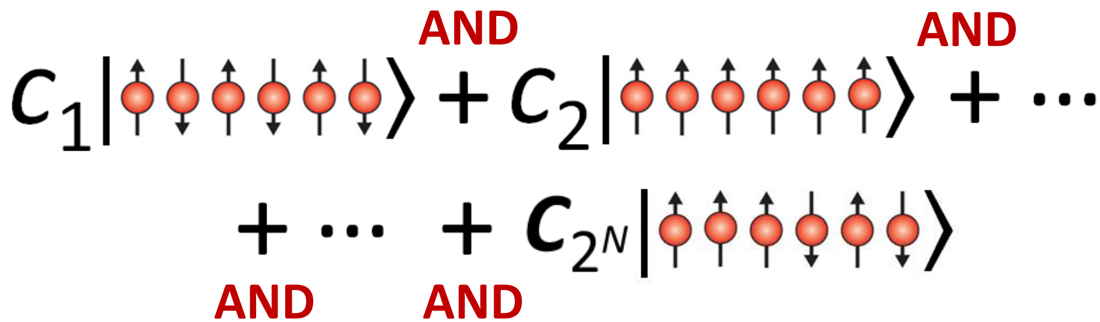
Downstairs in Alex's research lab ☺

Describe a N-bit state: classical vs quantum

Classical state:
N parameters



Quantum state:
2^N parameters



"Superposition": 2^N configurations <u>simultaneously</u>!

Exponential resources required to describe quantum systems on classical computers!

"Summit" Supercomputer at Oak Ridge National Lab

Power	13 MW
Storage	250 PB
Speed	200 petaflops

(Peta = $10^{15} \sim 2^{50}$)

State of the art < 60 spins

Adding each *one* extra quantum spin:
Double the required classical resources

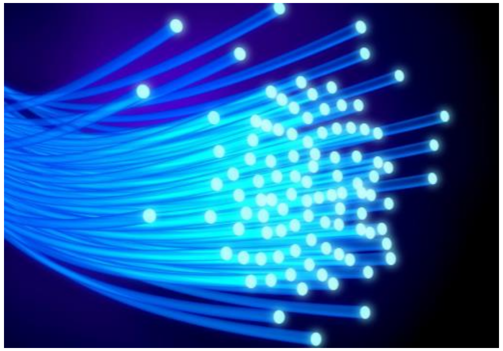
2^N

What does it take to simulate 300 quantum spins?

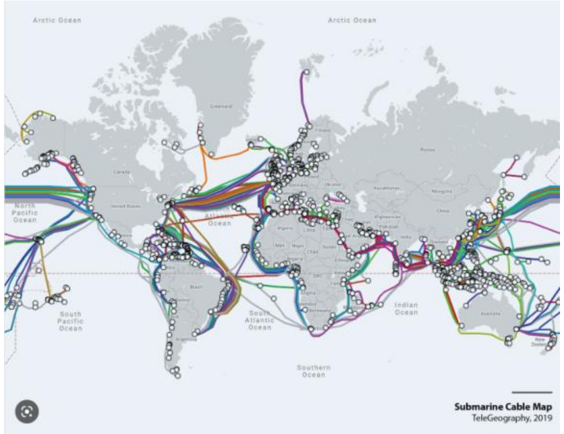
Estimated number of proton/neutron in our universe < 2^{300} …

Quantum Communication

Light as a precious resource for communication

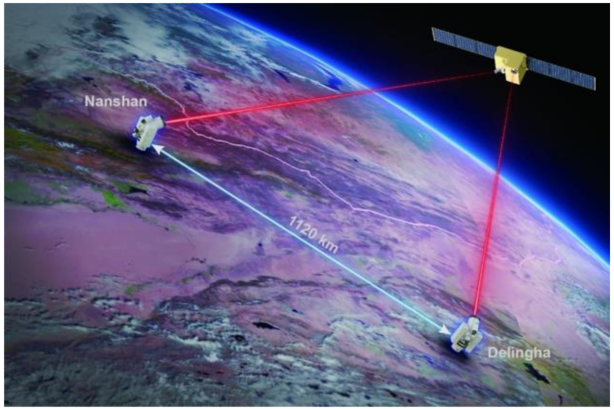


- Fiber optics revolutionized communication using light as carrier of information
    - Fast travel
    - Fast processing
    - High bandwidth



- Quantum light (photons) carry quantum information

- Using photons, secure communication is fundamentally guaranteed

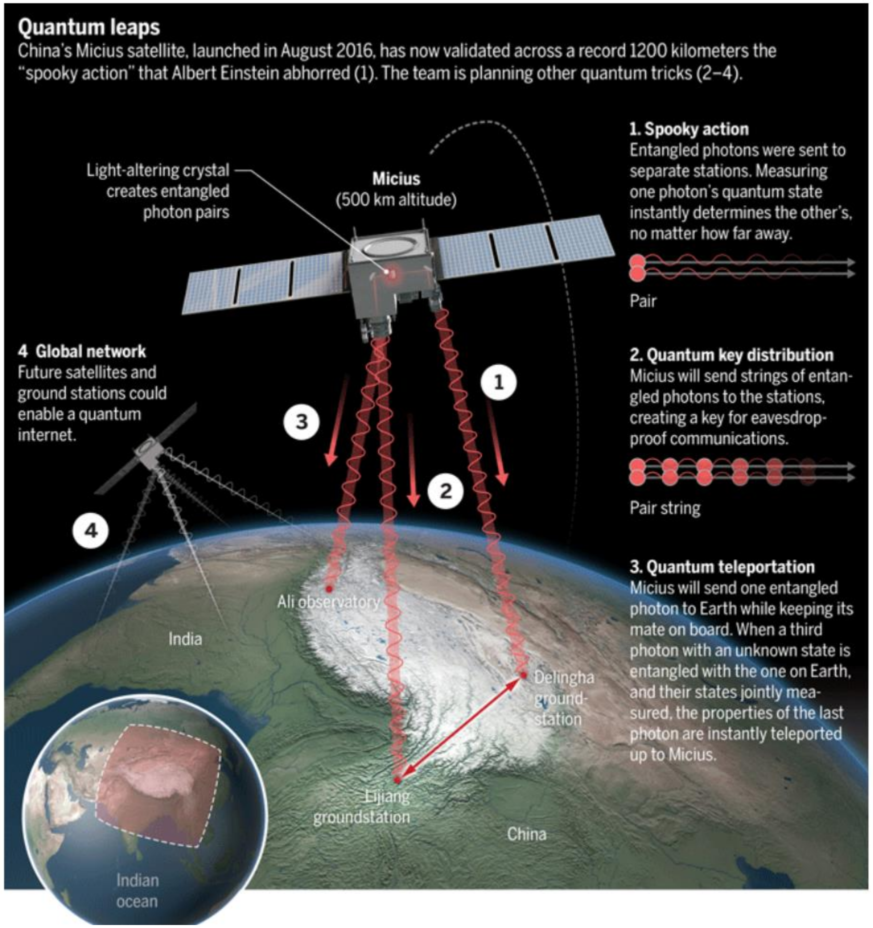


Quantum Communication

- Applying laws of quantum mechanics to information and communication
- Fundamentally secure – great importance to national security, financial institutions etc.
- Building towards a future quantum internet

Mode of optical communication:

- Free-space
- Fiber
- Satellite



https://www.science.org/content/article/china-s-quantum-satellite-achieves-spooky-action-record-distance

Quantum information encoded in:
Photon polarization, time, frequency, etc…

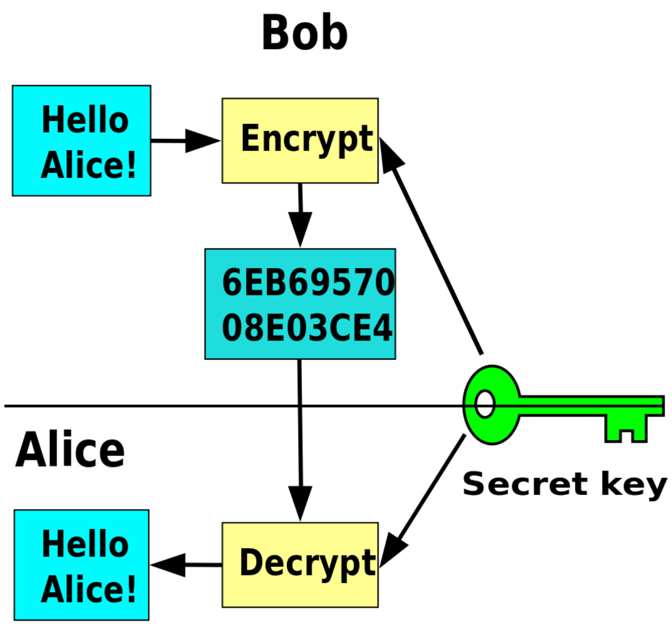
Cryptography

How to communicate securely..

Need secure *key distribution*

Binary Addition Table

0	1	0	1
+ 0	+ 0	+ 1	+ 1
= 0	= 1	= 1	= 0



Letter	Q					M				
Data Bit	1	0	0	0	0	0	1	1	0	0
Key Bit	0	1	1	0	0	1	0	0	0	1
Encrypted Bit	1	1	1	0	0	1	1	1	0	1

Transmit

Received Bit	1	1	1	0	0	1	1	1	0	1
Key Bit	0	1	1	0	0	1	0	0	0	1
Data Bit	1	0	0	0	0	0	1	1	0	0
Letter	Q					M				

*Want key to be completely **random**, and **private (secure)***

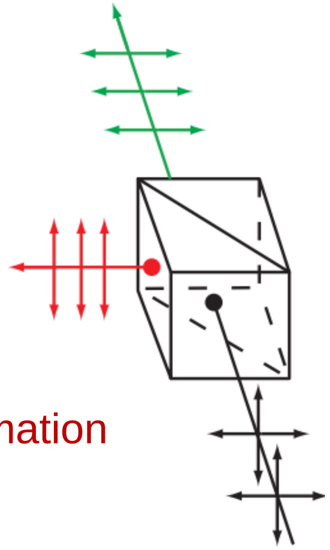
Quantum Cryptography

Quantum key distribution (QKD):
fundamentally secure against eavesdropping

Any attempt to eavesdrop ("measure") will change the quantum state of the transmitted information and can be detected.

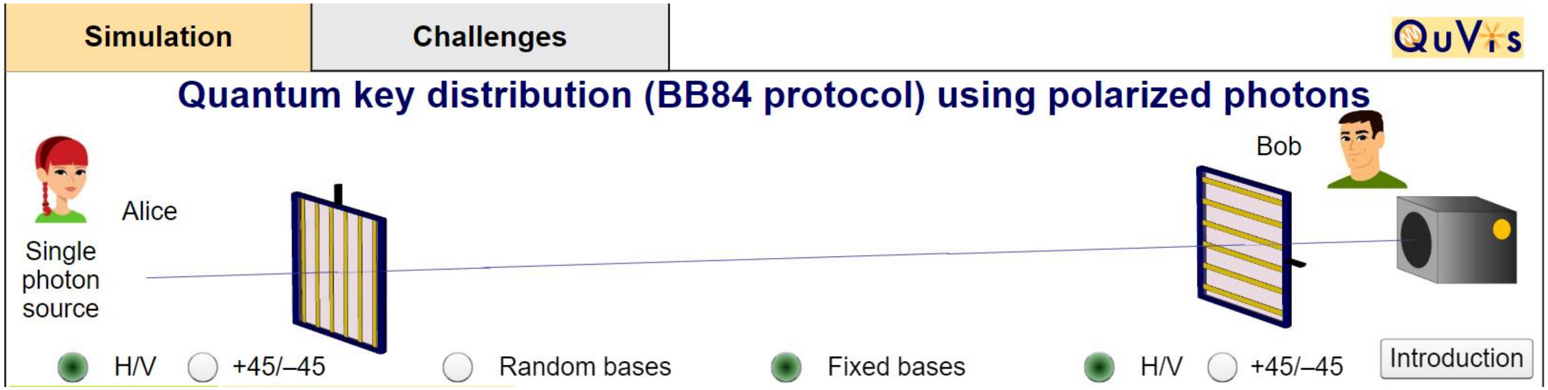
Setup:
Alice and Bob need to share a secret random sequence of 0s and 1s (to use as the secure key), but they cannot meet in person.

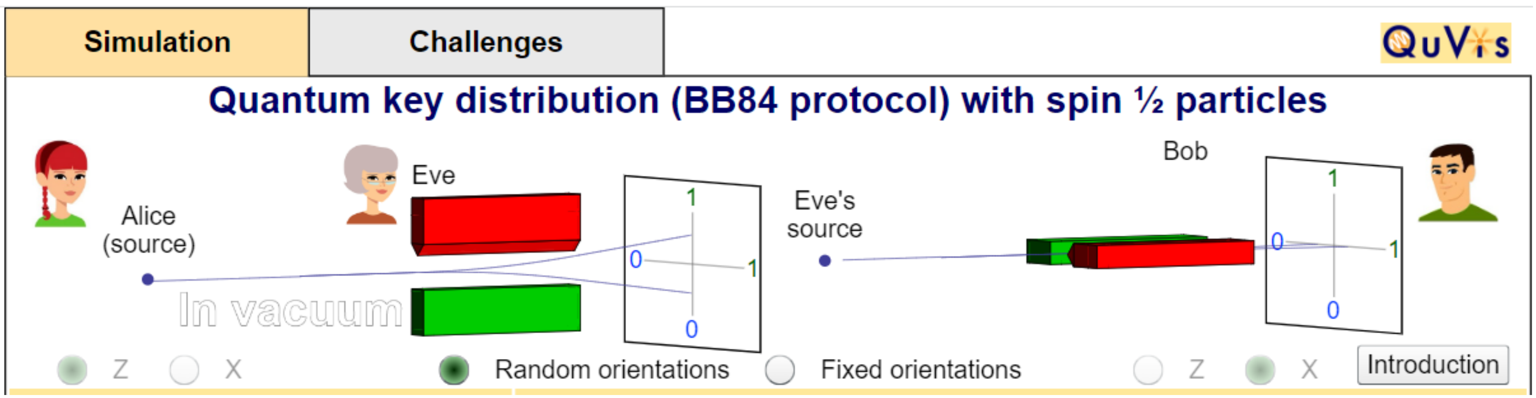
Quantum solution: BB84 (first quantum cryptography protocol, Bennett-Brassard 1984)



For optical quantum communication: the quantum information is typically encoded in the polarization of photons

Quantum Cryptography – BB84





https://www.st-andrews.ac.uk/physics/quvis/simulations_html5/sims/cryptography-bb84/Quantum_Cryptography.html

Quantum Cryptography – BB84

Goal: to transmit a bit string to be used as secure key

1. Alice transmits her bits (encoded in spin-up or spin-down) by randomly switching between two axes of the Stern-Gerlach Apparatus (SGA) (x or z)

2. Bob records the results (spin-up or spin-down) using a random choice of the measurement axes (x or z)

3. Alice and Bob publicly shares their choice of the SGA axes when transmitting/receiving the bit string (but not the values!), and keep only those values for which their axes were the same – these are the “trusted bits”.

4. Eve: intercept, measure in x or z, then send a new spin to Bob

5. Alice and Bob exchange a small number of their values from the trusted bits (which they then discard) to check for errors.

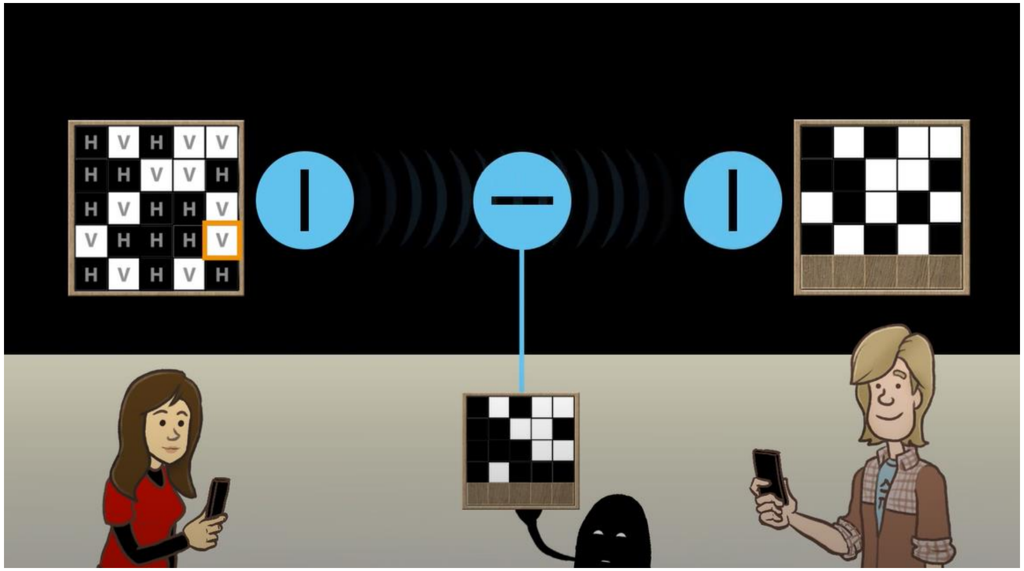
6. If the error rate < **25%**, the quantum communication was secure. They can use the rest of the trusted bits as a secure key for en-/de-cryption.

Quantum Cryptography – BB84

When do errors occur?
Eve measures in wrong direction, and subsequently sends in the wrong direction to Bob

Basis used by Alice and Bob	Basis used by Eve	Error?	Bits match for Alice and Bob
z z	z	No	100%
z z	x	In part	50%
x x	z	In part	50%
x x	x	No	100%

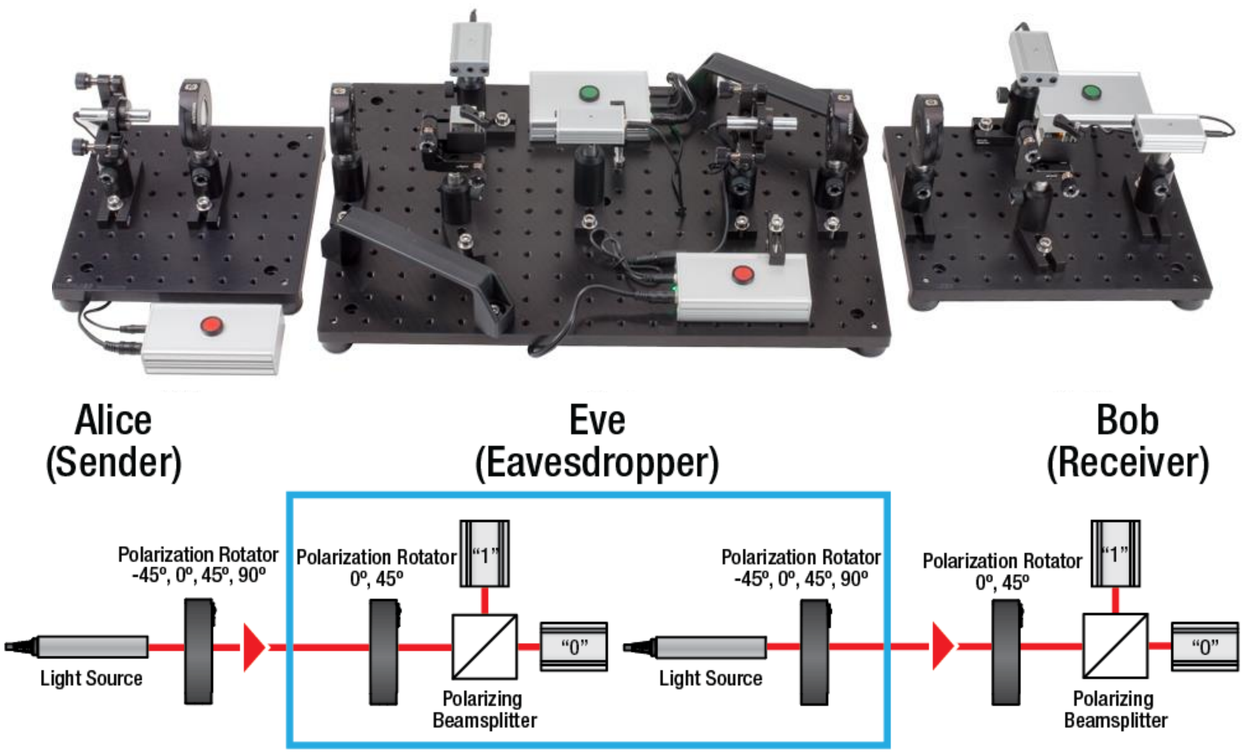
P_{error} = P (Eve measures in wrong axis) * P (Bob measures in "wrong" axis) = 50% * 50%



AM

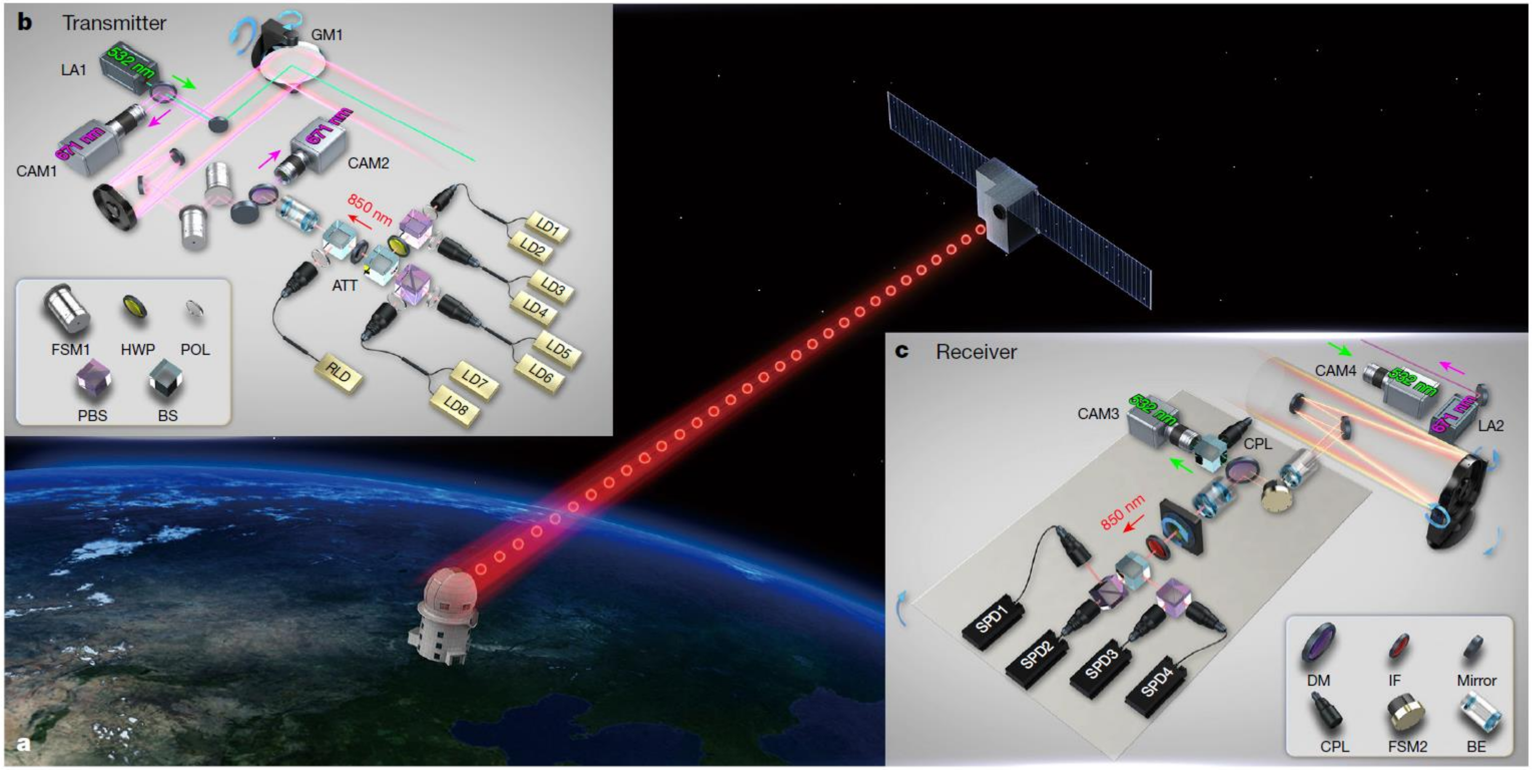
Quantum Cryptography – BB84

Implementation – require single photon sources to guarantee security, but does not require entangled photons



https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=9869

Satellite-to-ground quantum key distribution



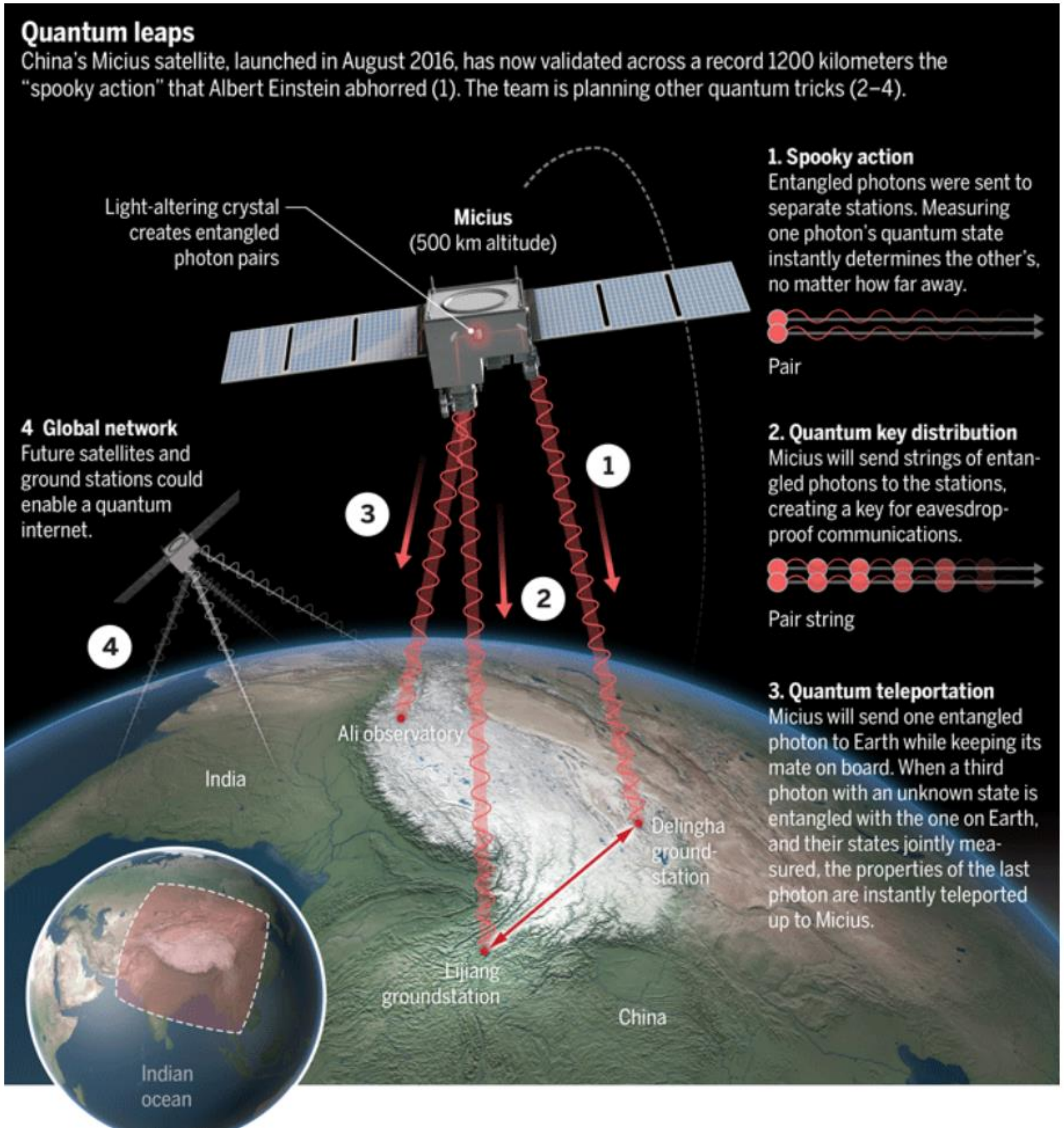
2017: … achieve a kilohertz key rate from the satellite to the ground over a distance of up to 1,200 kilometres

https://www-nature-com.ezproxy.lib.purdue.edu/articles/nature23655

AM

Quantum Communication

Recall: No-cloning



1. Entanglement distribution
2. Quantum Key distribution
3. Quantum teleportation

https://www.science.org/content/article/china-s-quantum-satellite-achieves-spooky-action-record-distance

Near perfect teleportation?

The first experiment succeeds only 25% of the time, without sending the measurement result to Bob.

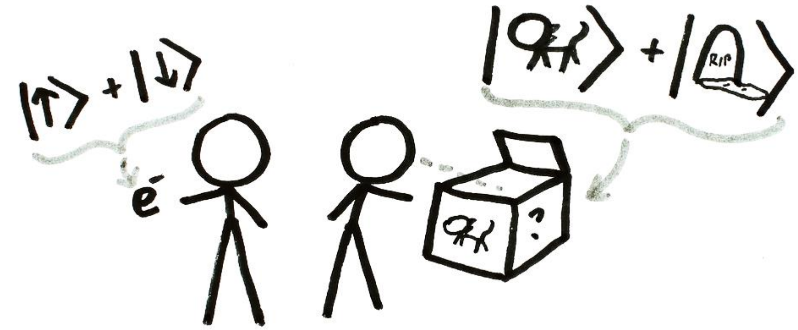
Current record for photon: 90% success rate, over hundreds of miles.

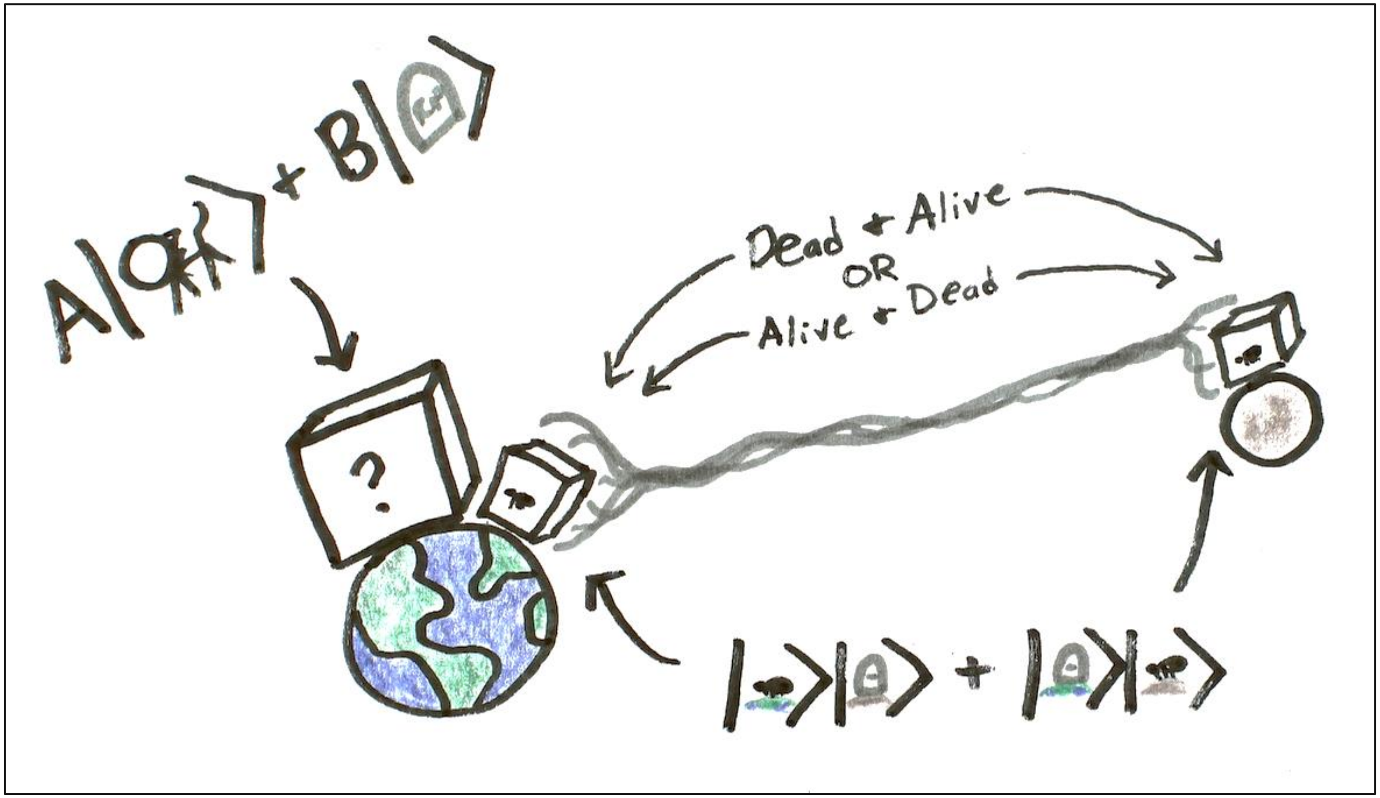
What if the teleported photon (X) **was entangled with another photon** (called C)**?**

→ After the teleportation, the photon Bob has will now be entangled with C.

Teleport Schrodinger's Cat

https://youtu.be/DxQK1WDYI_k (How to Teleport Schrödinger's Cat) – this video covers all the math of teleportation in a very accessible way





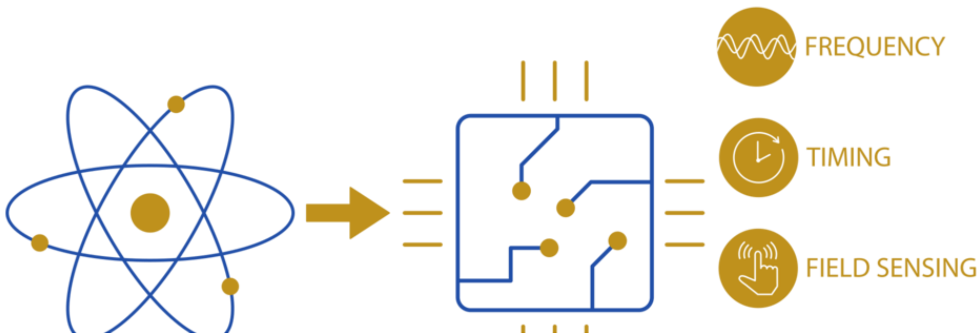
Quantum teleportation of larger objects?

- **Entanglement generation and distribution**
  - Atoms, molecules, buckyballs C_{60}, BEC, … bigger?
- **Decoherence**
  - Quantum mechanics in hot and messy environments?
- **Bell-state measurements…**

The Universe Is Always Looking
https://www.theatlantic.com/science/archive/2018/10/beyond-weird-decoherence-quantum-weirdness-schrodingers-cat/573448/

Quantum Sensing

Use quantum mechanical effects such as interference and entanglement, to measure physical quantities with higher accuracy and sensitivities.



Quantum sensors: can be built from different physical resources: atoms, ions, light, solid-state quantum devices, etc..

They are sensitive to: external effects such as rotation; acceleration; time; and electric, magnetic, and gravitational fields…

Example: external force/potential → E_n change : $\hbar\omega = E_n - E_{n-1}$

Applications for quantum sensing

Bioimaging
Neural sensing and heart imaging

Spectroscopy
Imaging of molecular structures such as proteins

Communication
Signal receiving and amplification for radar communication; calibrating electrical standards to support 5G/6G

Navigation
Providing high-accuracy GPS; assisting with navigation inside buildings and underground

Single molecule MRI using diamond

Atomic clocks

Environmental monitoring
Predicting volcanic disruption and measuring CO_2 emissions

Infrastructure monitoring
Monitoring mechanical stability and detecting leaks

Geographical surveying
Assisting with the location of oil and gas

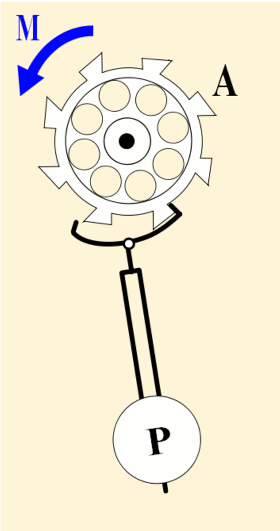
Fundamental science
Accessing high-energy physics beyond the standard model

Cold atom interferometers

LIGO – “hearing” black holes

https://www.mckinsey.de/

Atomic clocks

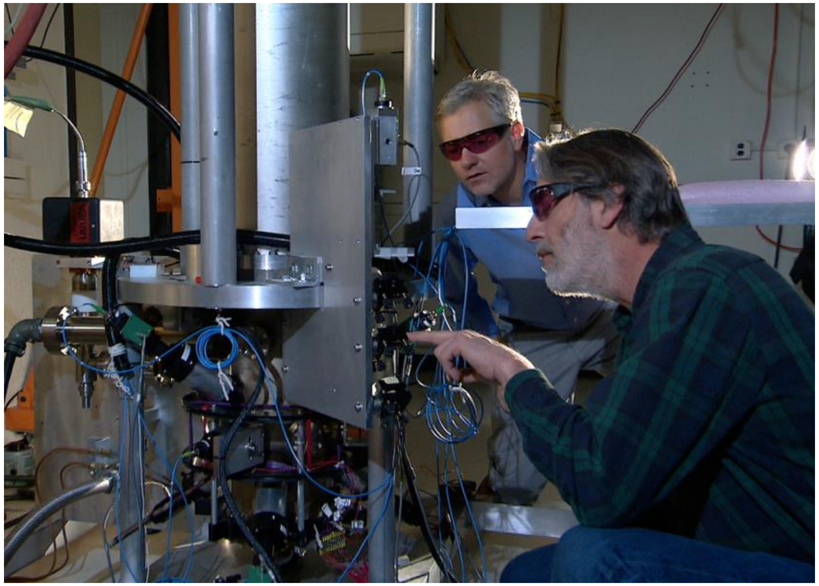


Time keeping: How is “1 second” defined today?

The frequencies of atomic transition are so reproducible that the definition of the second is now defined by a transition in Cesium-133:

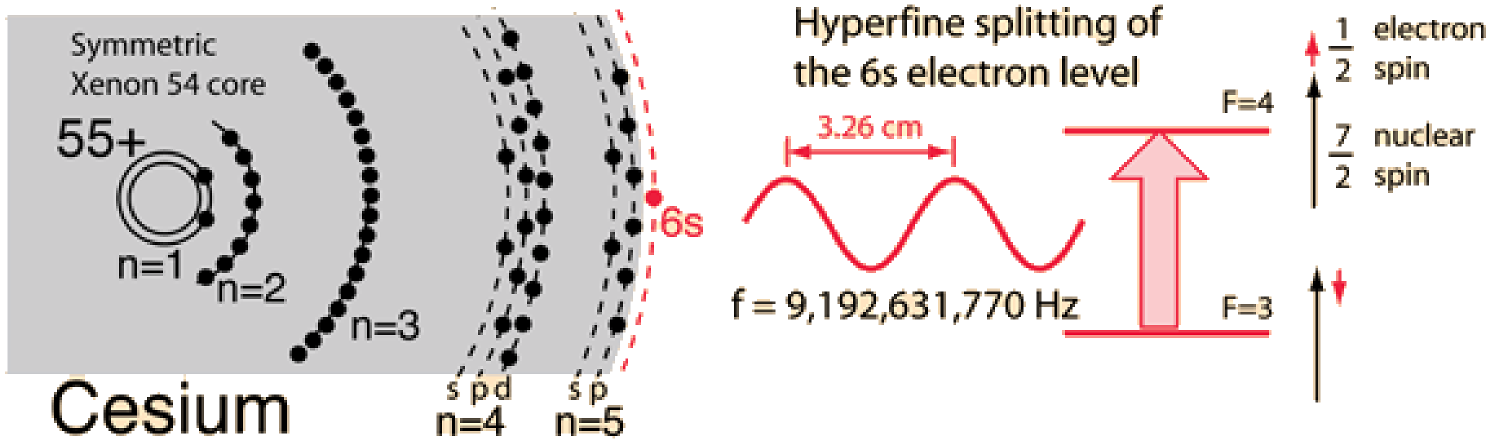
1 second = 9,192,631,770 cycles of the standard Cs-133 transition

(Since 1964; Prior to 1964: based upon the orbital period of the Earth.)



NIST-F2 cesium fountain atomic clock, civilian time standard for the United States.

Atomic clocks



Note: hyperfine splitting ~ GHz ~ 10^{-5} eV

Cs clock: transition frequency is in the microwave region, convenient for locking to a microwave oscillator.

Current stability (NIST-F2): one second in 80 million years

AM

http://hyperphysics.phy-astr.gsu.edu/hbase/acloc.html#c2

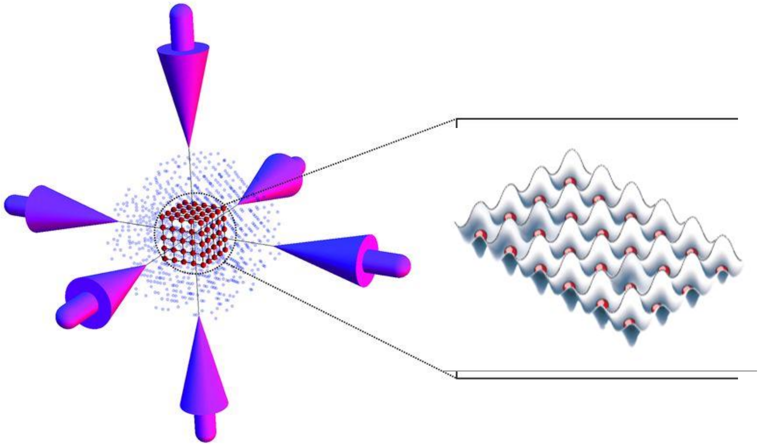
How to make better atomic clocks?

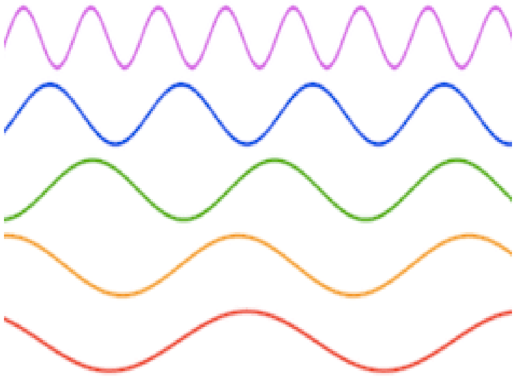
1. Need a better "pendulum"

- Transition frequency broadened by atomic motion (Doppler effect)
- Affected by external fields and potentials
- Affected by atom-atom interactions

2. Need more signal (more atoms, and measure for longer)

3. Need a better (finer) "ruler"
- Microwave transition (Cs clock): few GHz
- Optical transition: 100 THz





Ultracold atoms in optical lattices

+

Most stable optical laser

Most accurate clock

Best "Optical lattice clock":
Lose 1 second in 15 billion years (in 2019)

Age of universe:

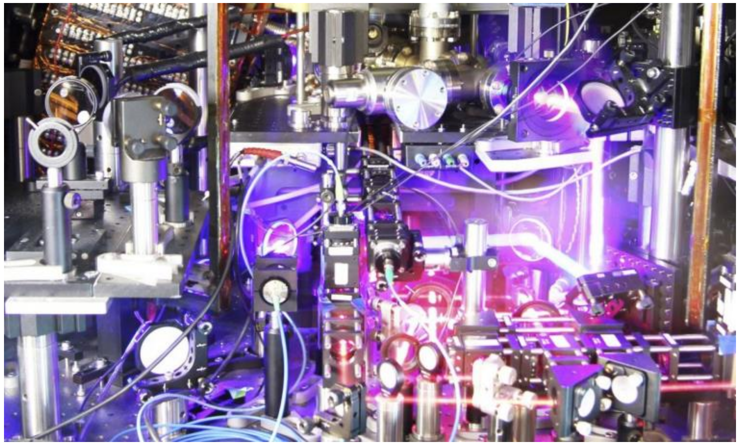
What use is a clock this accurate?

To use it as a quantum sensor, to measure the world around it, and to look for new physics!

Both at the smallest and largest length scales:

- subatomic interactions
- gravity and relativity

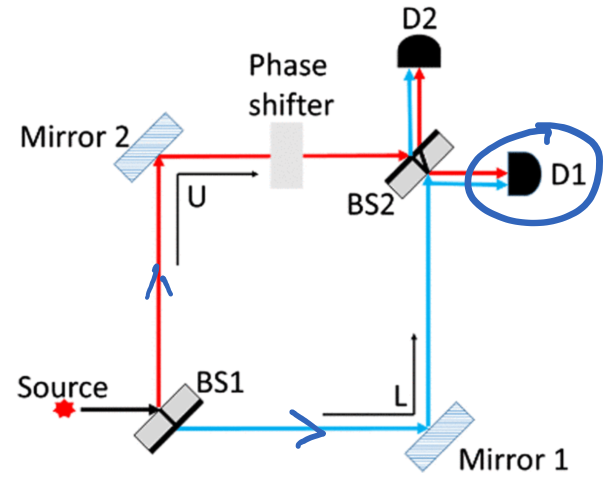
This clock can sense a change in height of few centimeters due to earth's gravity



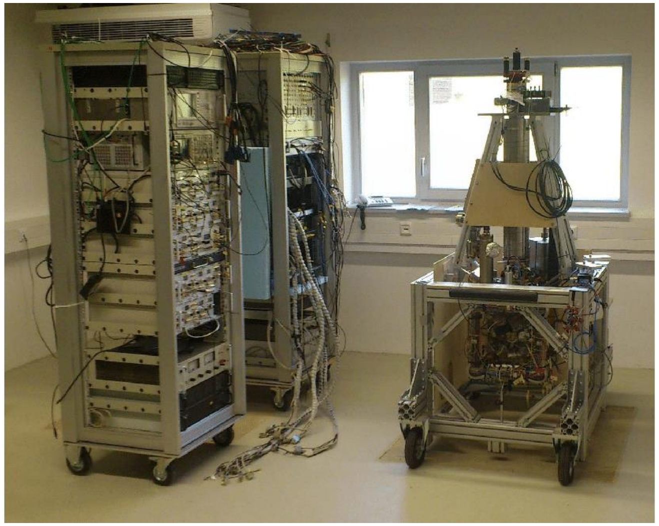
Jun Ye, NIST and CU Boulder - Breakthrough Prize in Fundamental Physics 2022

See also: https://www.youtube.com/watch?v=1JBHG6fipr4

Atom interferometers

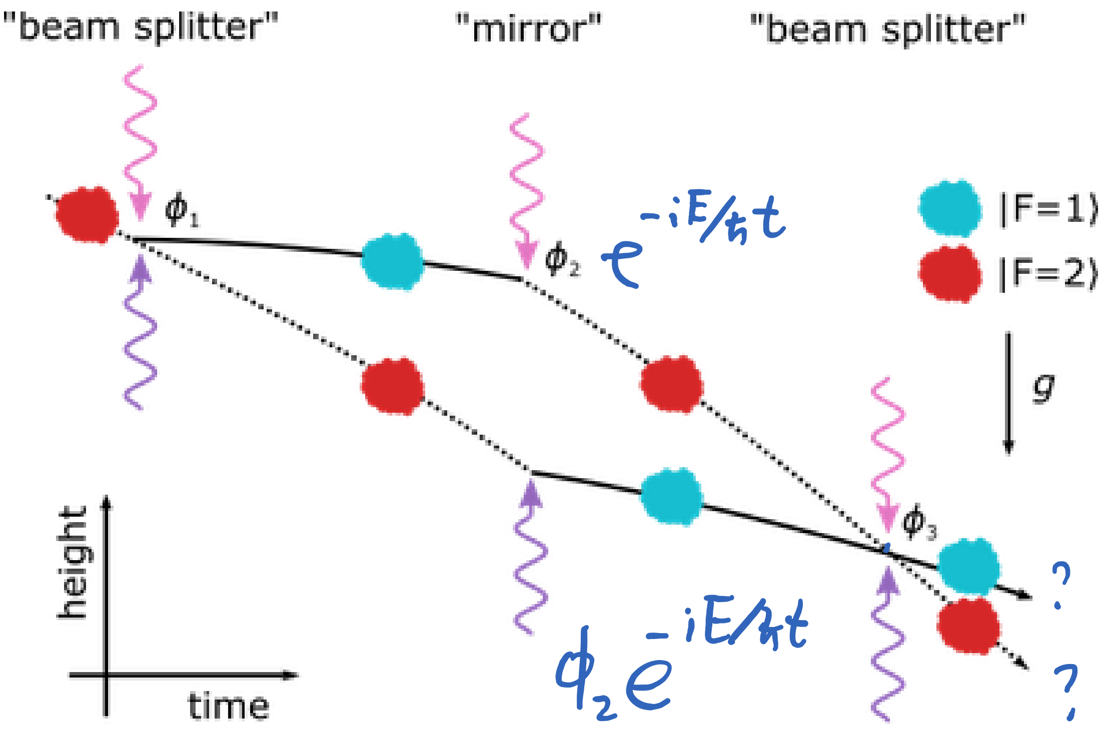


Another quantum sensor, that uses the wave properties of laser-cooled atoms (superposition, interference)

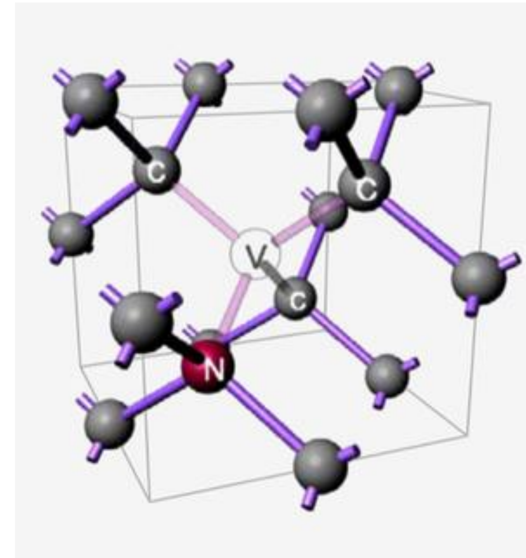


The mobile atom interferometer at the Geodetic Observatory Wettzell, Germany.

Inertia sensing; geo- surveying



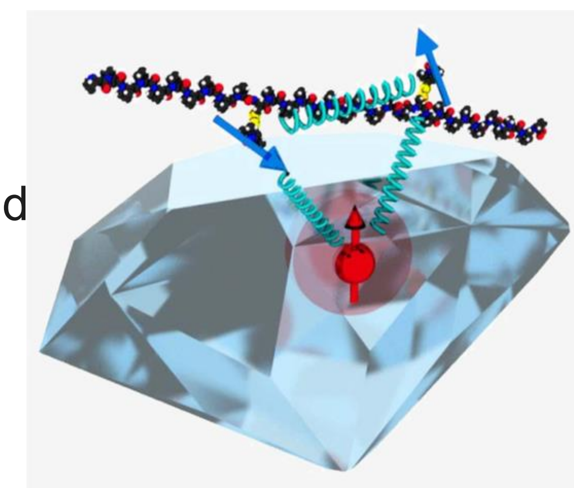
Quantum sensing with diamond



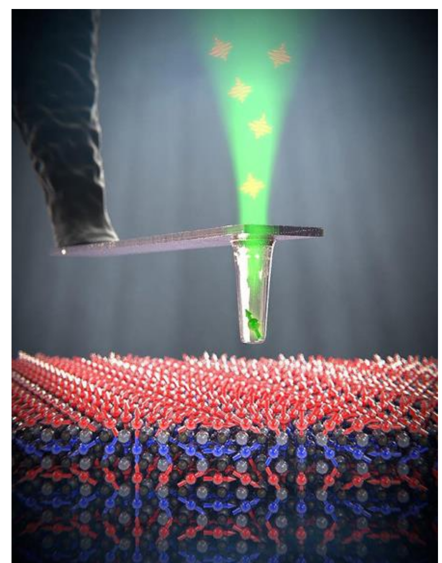
Why do some diamonds have a blue tint?
Boron impurities with discrete transitions

“Nitrogen-vacancy (NV) center” in diamond – Act like a quantum spin; control and detect using lasers and microwaves

Single-molecule MRI using NV center in diamond



Max Planck Institute



https://qnami.ch/

Scanning probe microscopy using a single NV center