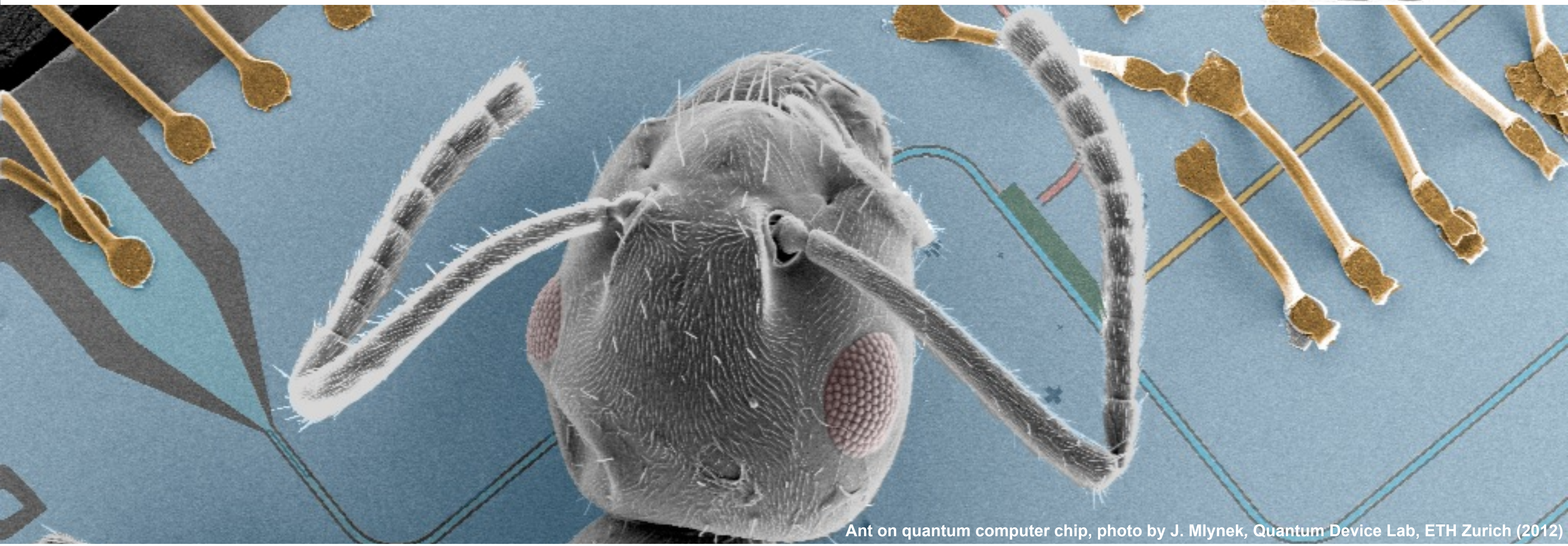
Taming quantum mechanics

Arne L. Grimsmo
The University of Sydney



Ant on quantum computer chip, photo by J. Mlynek, Quantum Device Lab, ETH Zurich (2012)

A brief history of quantum mechanics …

State of confusion, e.g. “is light particle of wave”?

Development of the Standard Model of particle physics

Boltzmann 1877:
suggests that atoms and molecules might have discrete “energylevels”

Max Planck:
(reluctantly) hypotheses the idea that atomic systems radiate discrete chunks of energy
E = h f

1900

Einstein 1905:
Light itself comes in discrete “quanta” of energy (later dubbed photons)

Niels Bohr 1913:
Formulates a description of atoms with discrete electron orbits (Bohr did not yet believe in photons)

Various phenomenological “quantum theories” emerge

1925

Heisenberg, Born & Jordan develop “matrix mechanics” and **Schrödinger** develops “wave mechanics”, later shown to be equivalent and today known as **quantum mechanics**

Paul Dirac late ‘20s: Unification of QM and special relativity.

1930

John von Neumann early ‘30s:
Rigorous mathematical formulation of QM

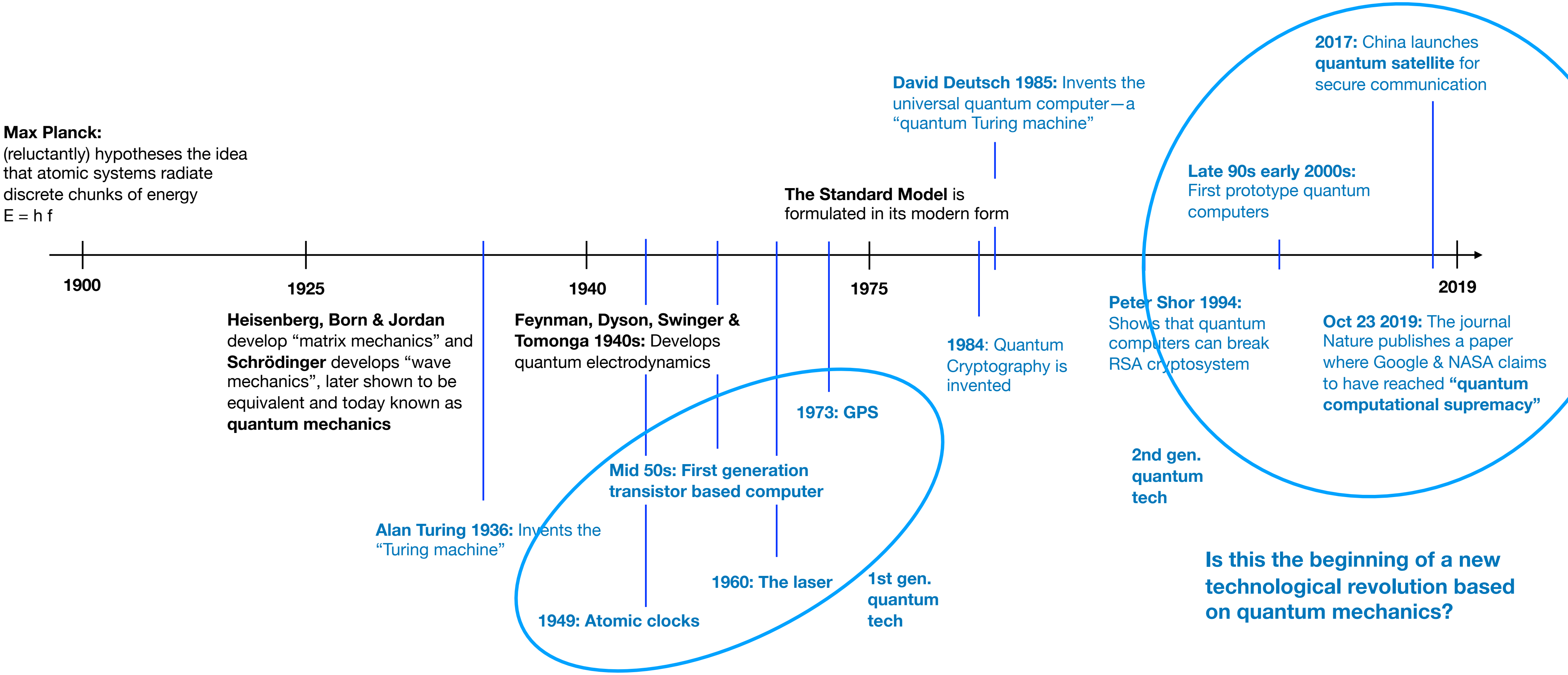
Einstein, Podolsky & Rosen 1939: Publishes a paper highly critical of quantum mechanics, “*spooky action at a distance*”

Feynman, Dyson, Swinger & Tomonga 1940s: Develops quantum electrodynamics

1975

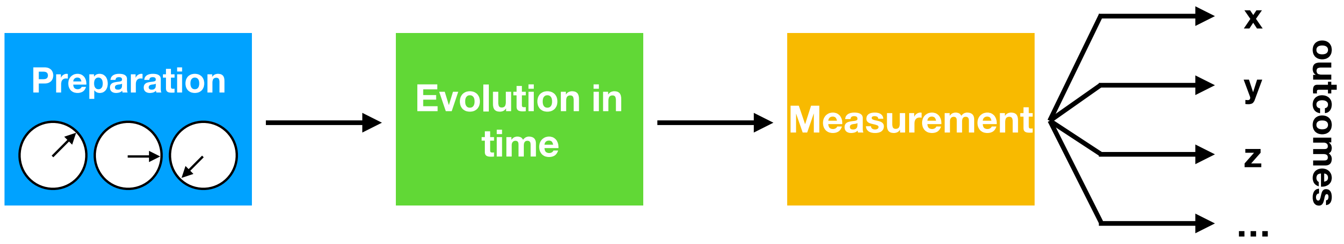
The Standard Model is formulated in its modern form

A brief history of quantum mechanics …
and quantum technology



So, what is quantum mechanics?

Let's take a step back. What do we want from a physical theory?



A physical theory should predict *outcomes* given a *preparation* of a physical system, possibly after some *transformation* (time-evolution)

Quantum mechanics is a framework for predicting the outcomes given a set of preparation settings

The rules of quantum mechanics

Quantum mechanics is often described as strange and counter-intuitive. This "quantum weirdness" comes from two facts

1. Outcomes in quantum mechanics are inherently random: the theory only tells you the *probability* of something happening

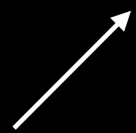
2. When something can happen in more than one way, the different possibilities *all* contribute to the final outcome

Plus, the rules for calculating the probabilities are… rather unusual…

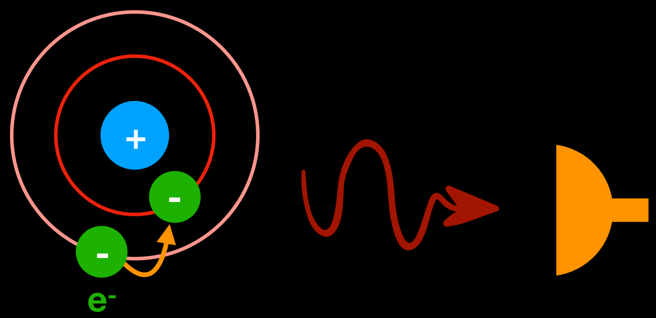
The rules of quantum mechanics

The probability of an outcome is described by a “complex number”. A complex number has both a *magnitude* and a *direction*

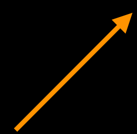
We can picture it as an arrow



Example: An atom decays, emits a photon, and a photon detector “clicks”



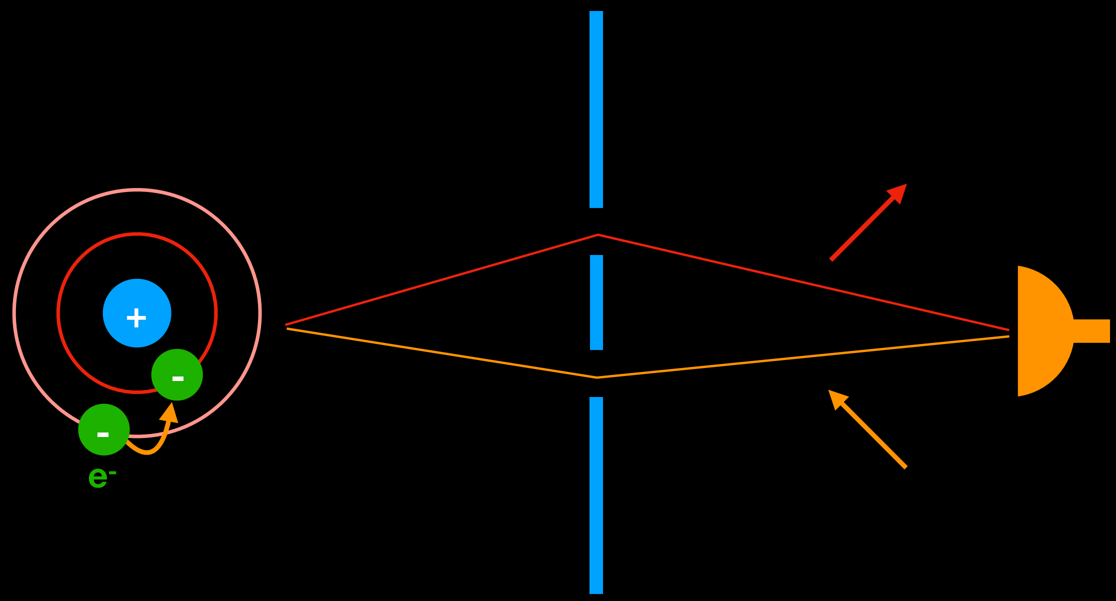
We represent the event “detector goes click” by an arrow



The length of the arrow represents the probability of getting a click

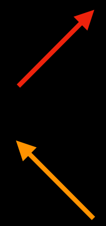
The rules of quantum mechanics

When something can happen in more than one way, the arrows have to be “added”



Path 1:

Path 2:



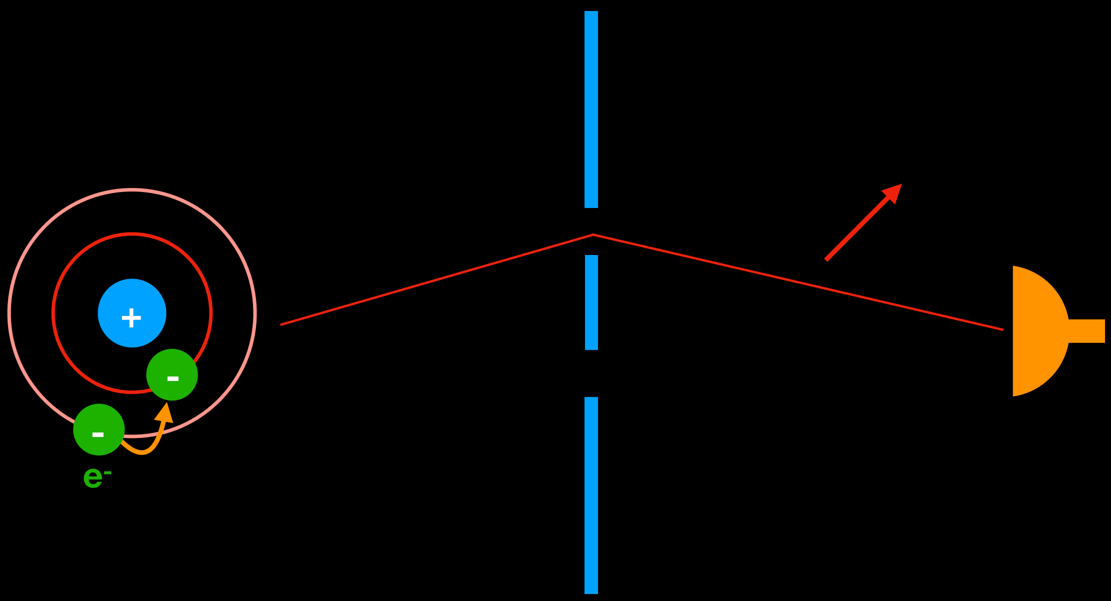
rule for “adding” arrows:

place the tail of one arrow at the head of the other

The total probability of a “click” is the length of the new blue arrow

The rules of quantum mechanics

What determines the direction of the arrows in the first place?



The arrows rotate in time, as the photon travels through space, at a frequency given by the photon's energy:

$$E = h f$$

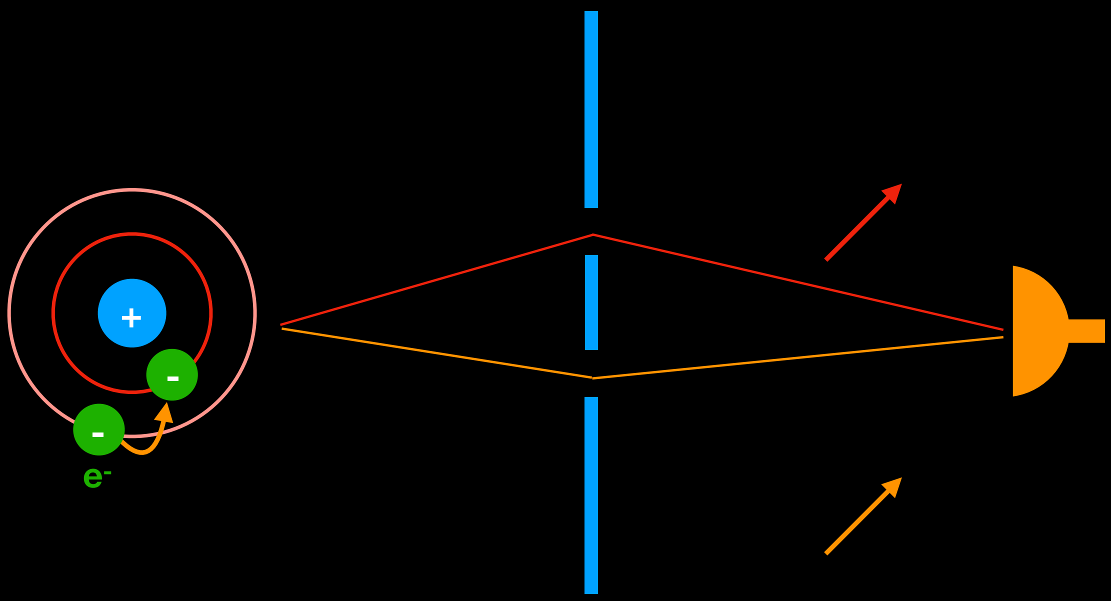
(h is the Planck constant)

For visible light, about 5×10^{14} rotations/sec

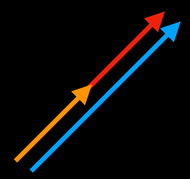
The angle of the arrow when the photon hits the detector thus depends on the distance from the atom to the detector

The rules of quantum mechanics

Constructive and destructive interferene



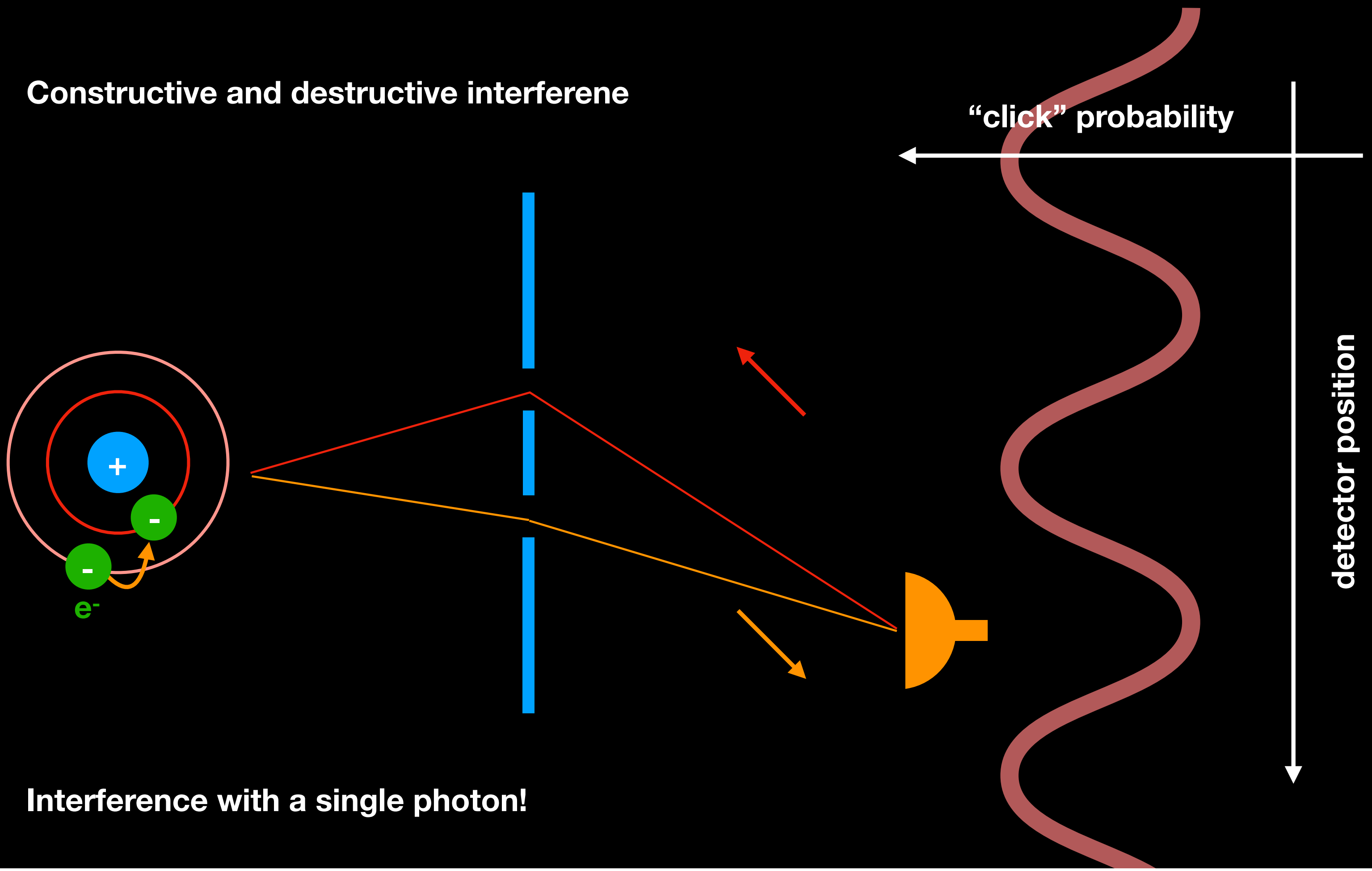
When the paths have the same distance, the arrows are aligned, and the lengths thus add up to one longer arrow:



The other extreme is if the arrow point in exactly opposite direction, in which case they cancel out:

The rules of quantum mechanics

Constructive and destructive interferene



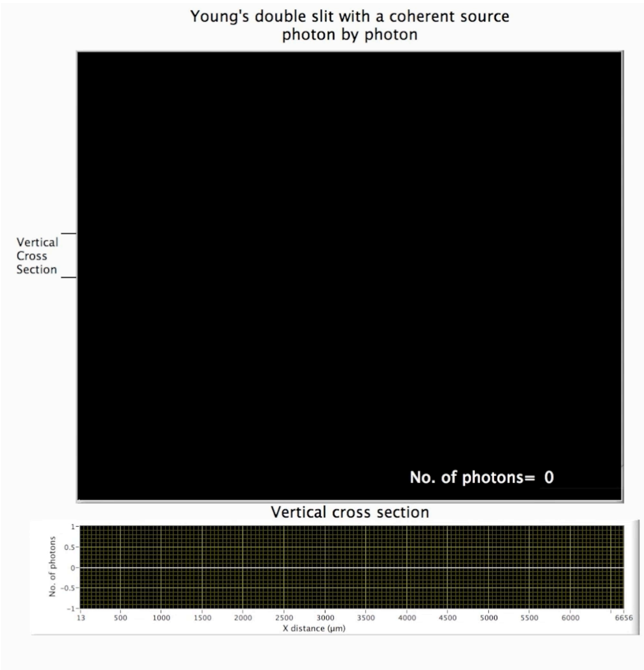
Interference with a single photon!

Double-slit experiments with single particles

Already in 1909 Sir Geoffrey Ingram Taylor performed a double-slit experiment (as we have discussed) was performed using an extremely weak light-source, weak enough that only a single photon would pass through the slits at a time. The physics was however not yet understood.

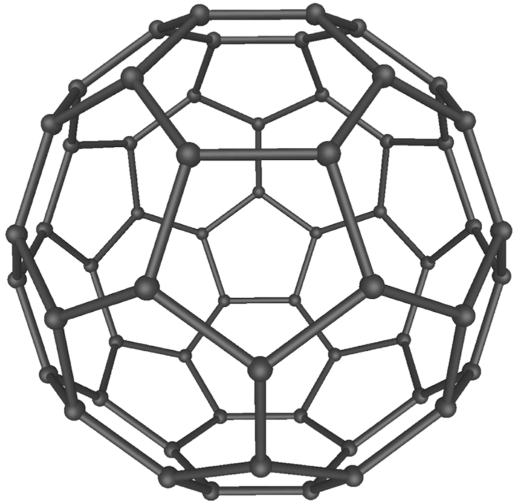
The following vide shows a modern version [R. S. Aspden, M J. Padgett American Journal of Physics 84, 671 (2016)]

The photon arrivals are recorded by an extremely sensitive camera (sensitive to a single photon!)



Double-slit experiments with single particles

By now, the double-slit experiment has been performed even with massive particles, such as electrons, large carbon molecules of ~1 nm size (C60 and others, aka “buckyballs”)



Question: Why do we not observe this with footballs or other macroscopic objects?

The rules of quantum mechanics

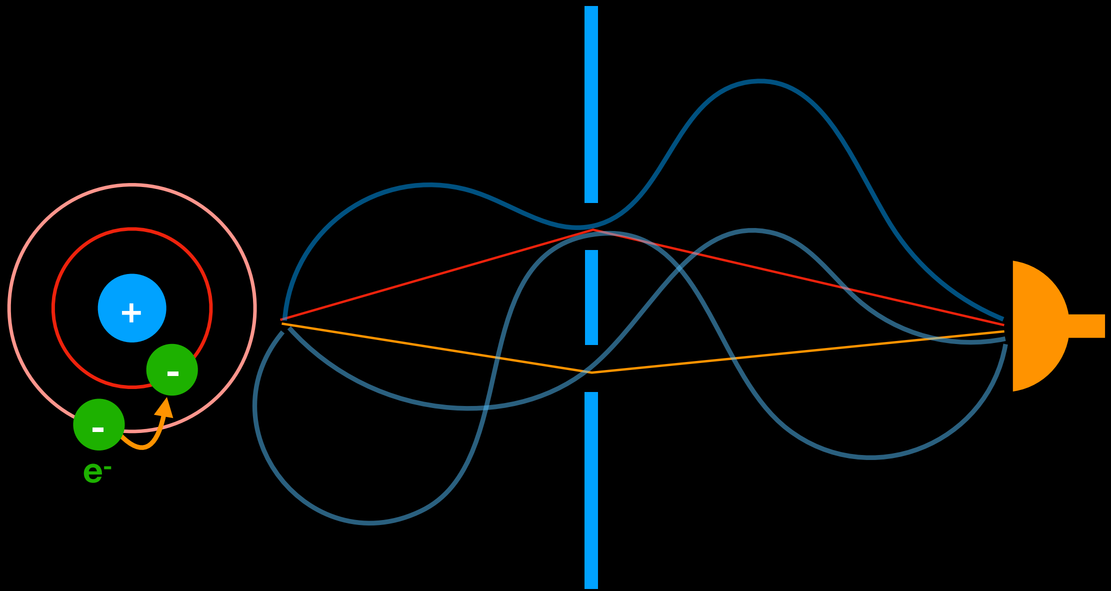
We can summarize the rules of quantum mechanics as follows:

1. To every possible way something might have happened, we associate an arrow

2. To find the probability of the thing happening, we “add up” all the arrows representing each way it can happen. The probability is given by the length of the resulting arrow after adding up

The rules of quantum mechanics

Note: In quantum mechanics, *all possible* pahts contrbute



It turns out, however, that most of these paths tend to cancel out, and the main contribution comes from the photon traveling along straight lines

From observing to controlling:
The beginning of a new quantum technology

From observing to controlling:
The beginning of a new quantum technology

The “founding fathers” of quantum mechanics, such as Bohr, Einstein and Schrödinger often used “thought experiments” to reason about quantum mechanics

They did not, however, think that these thought experiments could actually be performed…

"*We never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences*", Erwin Schrödinger in 1952.

From the 80s and onwards, however, experimentalists have achieved incredible control over single quantum systems, performing many of the “thought experiments” from the 1920s and 30s in the lab

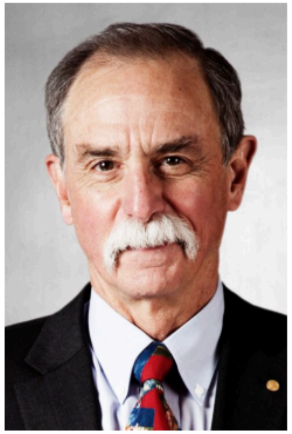
Two key research groups in this effort were a group in Paris led by scientist Serge Haroche and an American group led by David Wineland

Haroce and Wineland shared the 2012 Nobel Price in physics for this work

The Nobel Prize in Physics 2012

Serge Haroche

Prize share: 1/2



David J. Wineland

Prize share: 1/2

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems."

The Paris group's "photon box"

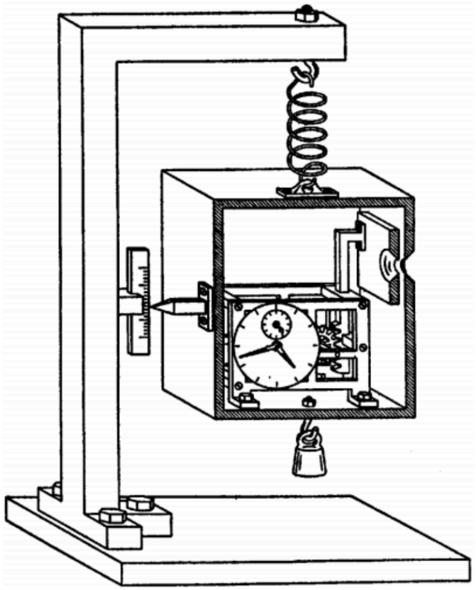
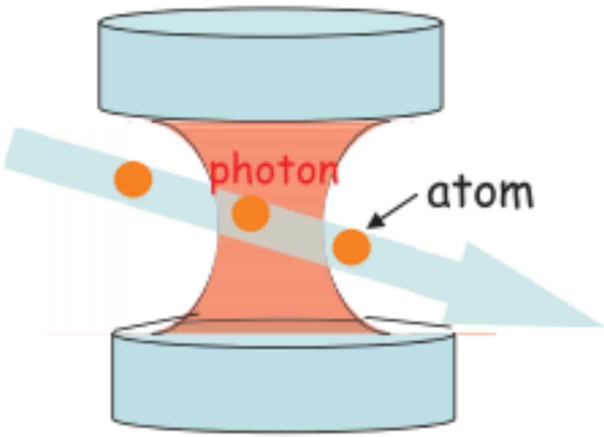


FIG. 1. The Einstein-Bohr photon box. From the Niels Bohr Archive.



Schematic illustration of the "photon box" used by the Paris group

A stream of atoms is used to control and manipulate photons trapped between two mirrors

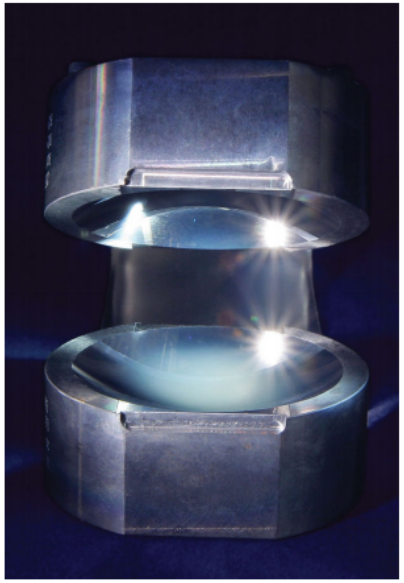


Photo of the Paris "photon box"

The mirrors are superconducting metal cooled to a few Kelvin to maximize reflectivity

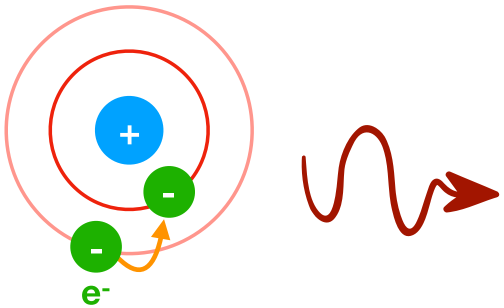
A single photon is trapped for about 130 ms

All figures taken from S. Haroche Rev. Mod. Phys. 85, 1083 (2013)

Taming photons

Haroche used atoms to control the number of photons trapped between the two mirrors

An atom initially in an excited state (electron in the outer orbit), will eventually decay (electron in the inner orbit)



By carefully tuning the time-of-flight from left to right, we can make sure the atom decays and emits a photon between the two mirrors, which will be trapped (for about 130 ms)

The opposite of this process can also be used to absorb photons

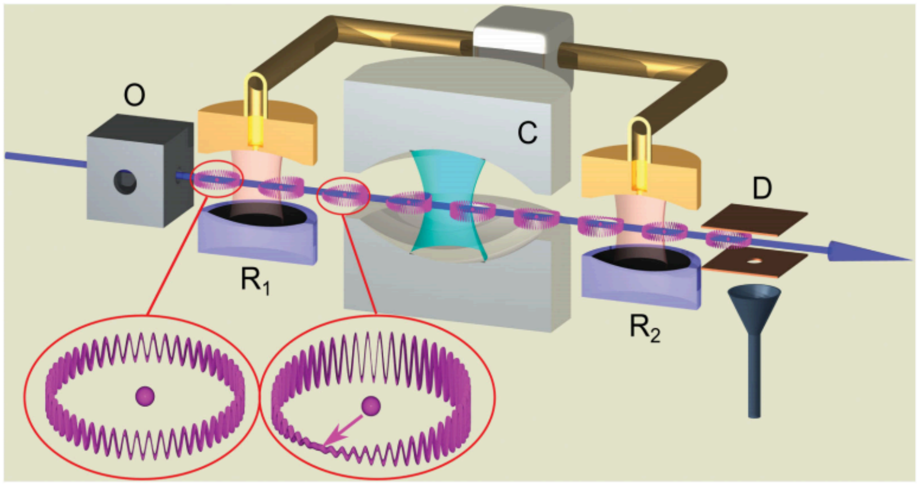


Figure from S. Haroche Rev. Mod. Phys. 85, 1083 (2013)

By sending atoms through the mirrors, and using a feedback mechanism based on measuring the number of photons inside the cavity (without destroying them!), the Paris group was able to stabilize a fixed number of photons, say 7, between the mirrors indefinitely

Schrödinger's cat: Dead or alive?

The Paris group also made a realization of the famous Schrödinger's cat paradox

FIG. 17 (color). The Schrödinger cat thought experiment. From "Science et Vie Junior."

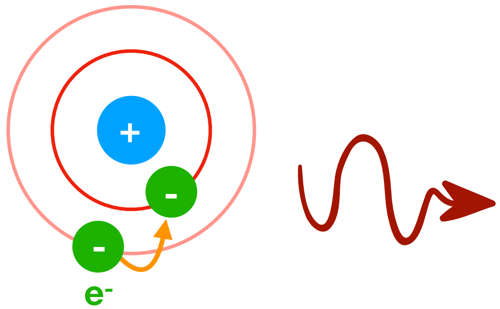
In Schrödinger's thought experiment an atom decays and emits a photon (or radioactive particle), which is connected to a trigger mechanism that kills the cat

According to QM: At intermediate times, the cat is in a superposition of dead and alive!

Initially the electron is in the outer orbit with certainty

After a sufficiently long time, it is in the inner orbit with certainty

At intermediate times the electron is can be in either orbit. In quantum mechanics, this is called a "superposition"—is is both, rather than either/or



Schrödinger's cat: Dead or alive?

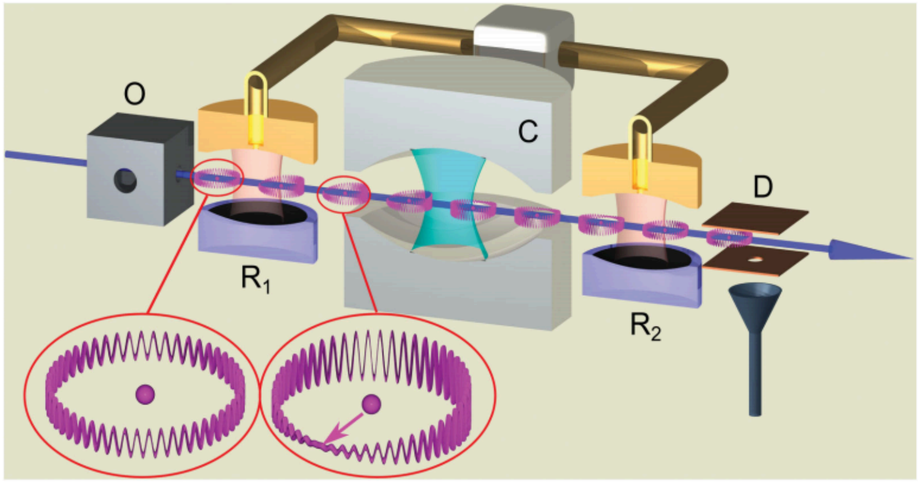


Figure from S. Haroche Rev. Mod. Phys. 85, 1083 (2013)

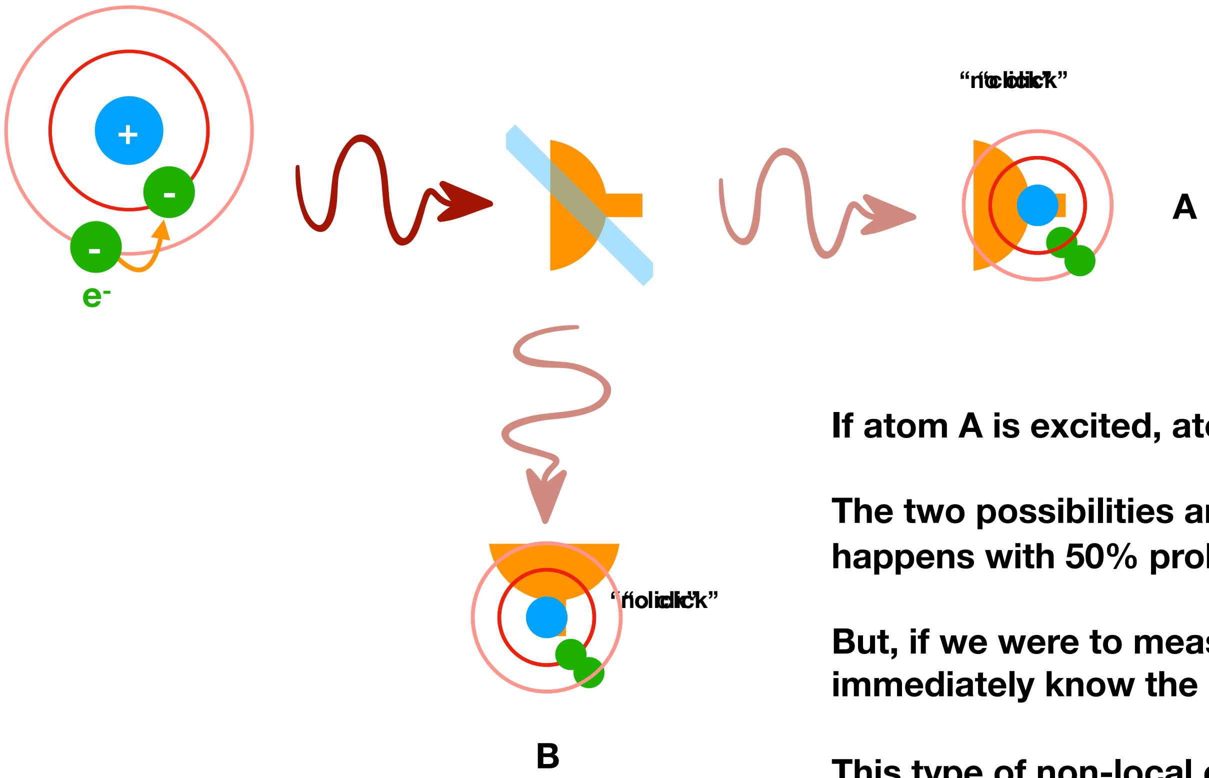
In the experiment, an atom was prepared in a superposition state and sent between the mirrors

The role of the "cat" was played by the standing mode light field

Measuring the atom after it passed between the mirrors left the light field in a superposition of two states

Crucially, the two states were macroscopically distinguishable, corresponding to two (reasonably) large electric fields oscillating out of phase

Entanglement
“spooky action at a distance”



If atom A is excited, atom B is not, and vice versa

The two possibilities are equally likely, each outcome happens with 50% probability

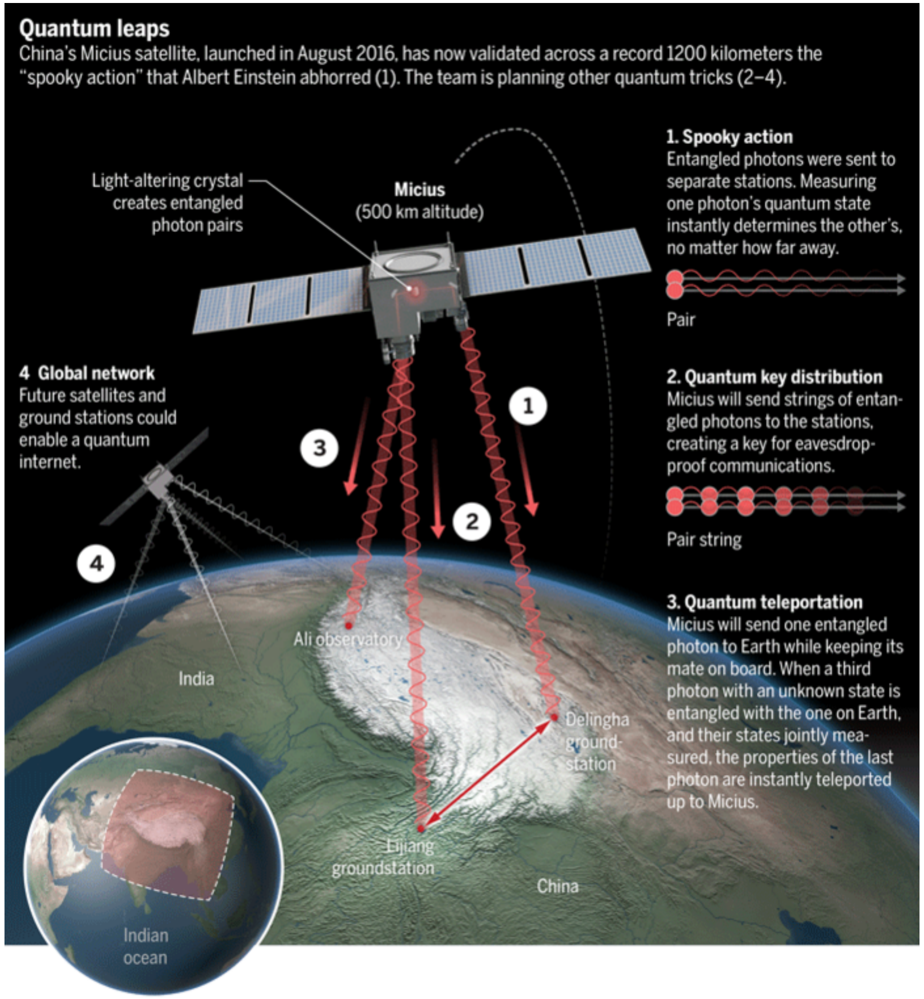
But, if we were to measure the state of atom A, we would immediately know the state of atom B!

This type of non-local correlation is called *entanglement*

A quantum satellite for distributing entanglement

The world record for distributing entanglement is held by a Chinese team

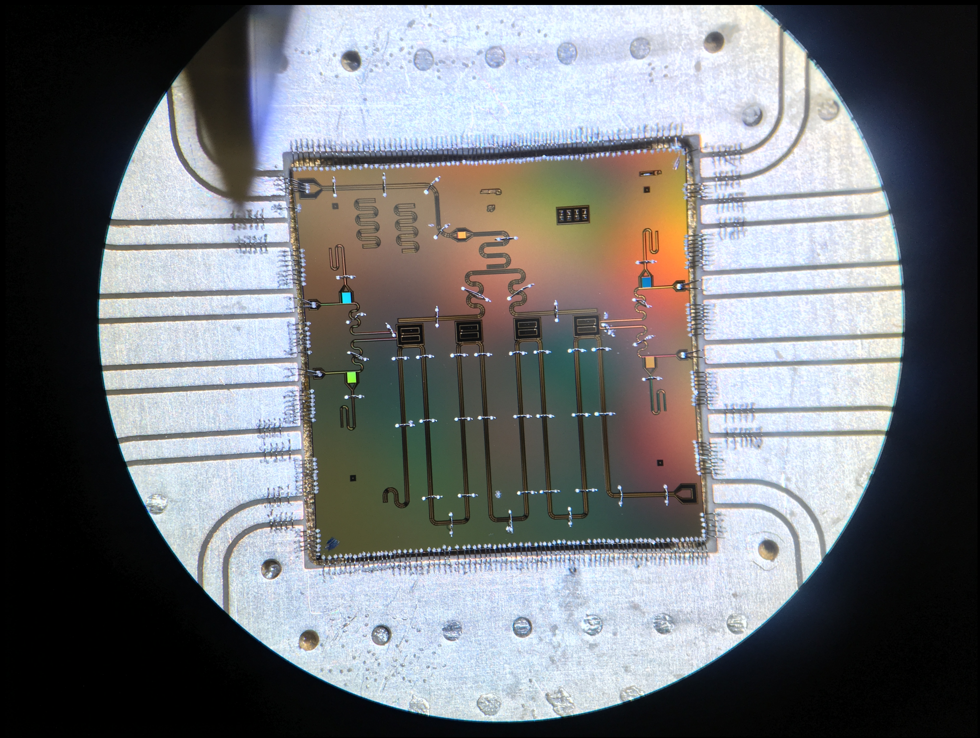
They generated entangled particles on board a satellite, which where then sent to two different ground based stations, 1200 kms apart



Entanglement can be used for secure communication, amongst other things

The goal is to build a "quantum internet" based on this principle

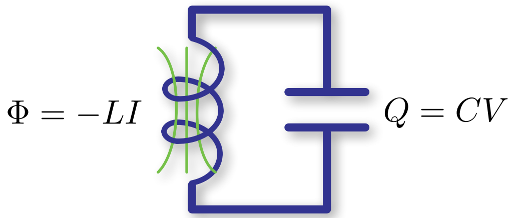
From atoms and photons to a new "quantum electronics"

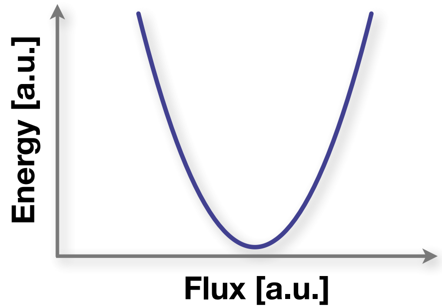


A quantum electronics chip made at UC Berkeley
Photo by courtesy of John Mark Kreikebaum, PhD student UC Berkeley

From atoms and photons to a new "quantum electronics"

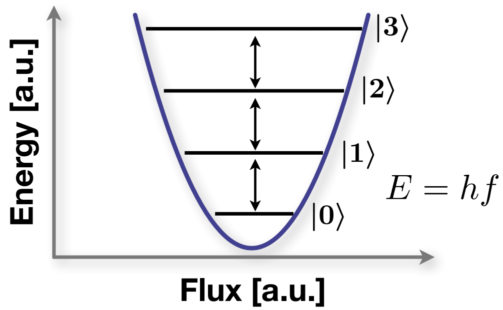
Are electrical circuits "quantum"?





Abstractly, the physics of this circuit is exactly equivalent to that of a particle moving in a parabolic potential

According to quantum mechanics, this electronic circuit should have discrete energy levels, just like an atom (the energy levels are the discrete allowed orbits of the electron)

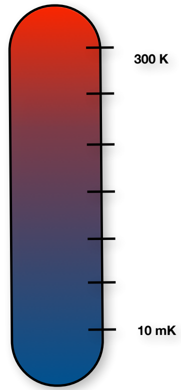


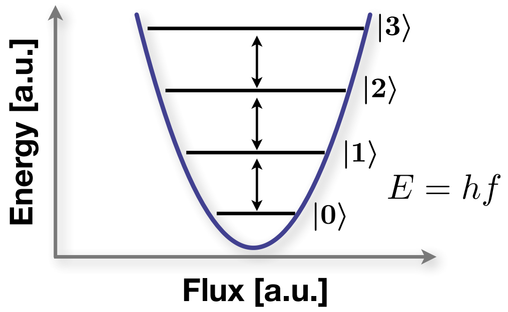
Entering the quantum world

To observe quantum behavior in such a circuit, we need two ingredients:

1. Cool the circuit down such that thermal photons are negligible

2. Use superconducting metal to avoid resistance, which dissipates energy

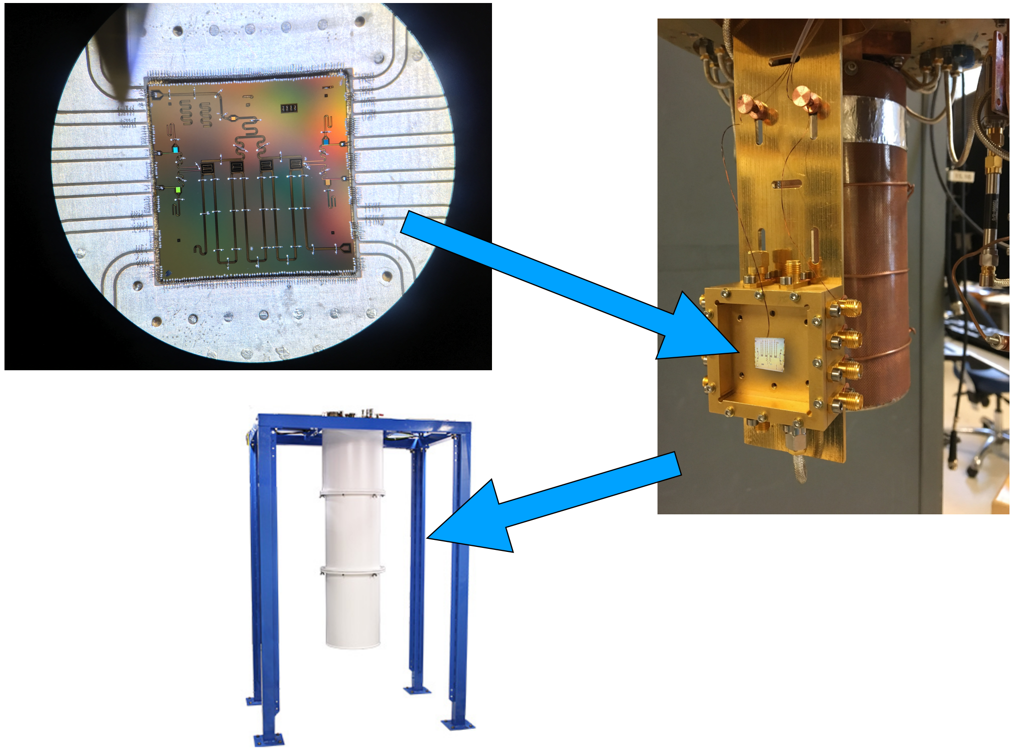




Typical quantum electronics experiments use aluminium cooled down to about 10 mK (much colder than outer space!)

The typical splitting of the energy levels, E = h f, corresponds to a frequency of f = 5-10 GHz. Remarkably this is very similar to the energy levels of the atoms used in the “Paris photon box”!

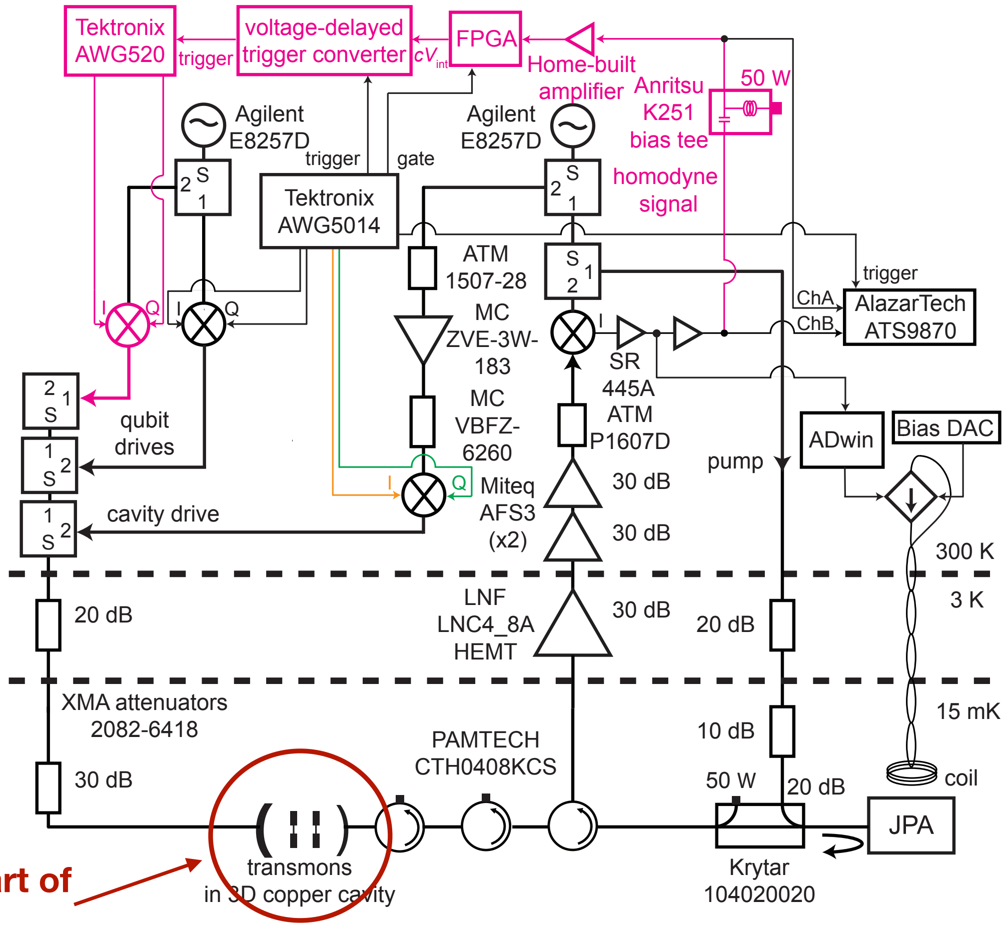
Entering the quantum world



Dilution refrigerators are routinely used to reach temperatures 10-50 mK

Schematic of a typical experimental setup

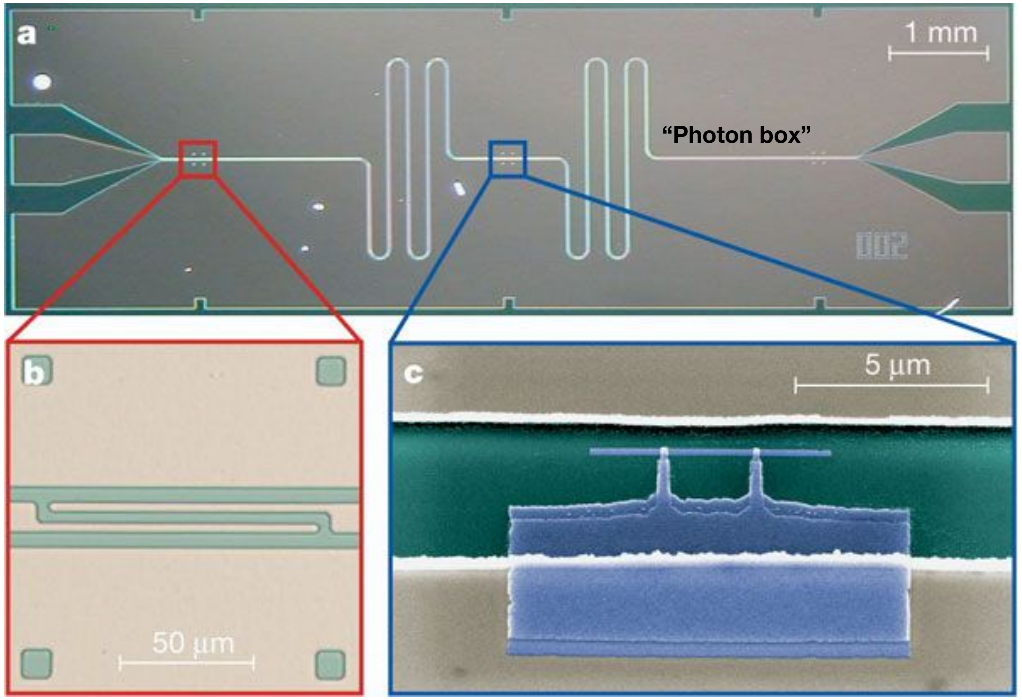
Entering the quantum world requires a lot of advanced non-quantum electronics!



This is the only "quantum" part of the experiment

The Paris “photon box” experiments can be reproduced using circuits printed on a chip

Standing waves of electrical current in a finite wire is analogous to standing electromagnetic waves between two mirrors



This capacitor plays the role of the “mirror” in the Paris experiments

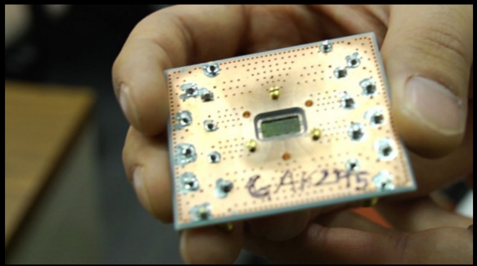
The blue structure is an "artificial atom”, playing the role of the atoms in the Paris experiment

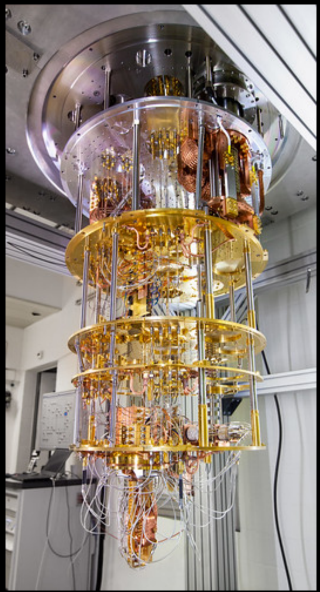
Note that this "artificial atom” is huge compared to a real atom

The next chapter: Quantum computers

Photos from ibm.com

The next chapter: Quantum computers





Photos from ibm.com

The race is on

Recently, a race has begun to build the first commercial quantum computer

The main players are IBM, Google, Microsoft, and startups Rigetti Computing, IonQ and PsiQuantum

The most advanced machines are built by IBM and Google, based on superconducting quantum electronics (these companies also have good PR departments, as evidenced by below headlines)

The New York Times

OUT THERE?

Quantum Computing Is Coming, Bit by Qubit

With transmons and entanglement, scientists strive to put subatomic weirdness to work on the human scale.

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Google claims to have reached quantum supremacy

Researchers say their quantum computer has calculated an impossible problem for ordinary machines

Madhumita Murgia and Richard Waters SEPTEMBER 21 2019

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Google claims to have built the first quantum computer that can carry out calculations beyond the ability of today's most powerful supercomputers, a landmark moment that has been hotly anticipated by researchers.

Save

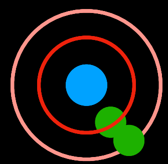
Quantum computing 101

Classical (i.e., "non-quantum") computing is described in terms of logical operations on strings of *bits*

A bit is a binary variable taking one of two values: 0 or 1

In a quantum computer, bits are replaced by "quantum bits" aka *qubits*

A qubit is any quantum system that can be in one of two states, call them "0" and "1"



However, according to quantum mechanics, any *superposition* of "0" and "1" is also allowed
(we sometimes write a superposition as "0" + "1")

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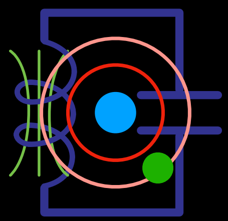

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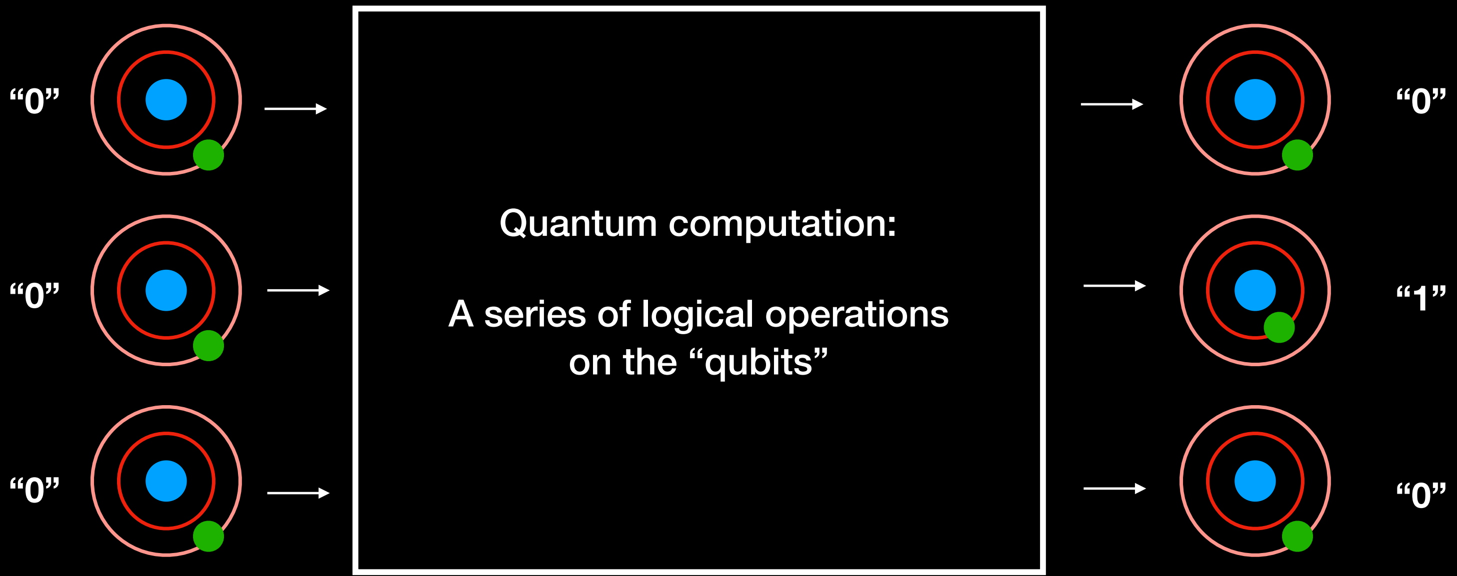
(we sometimes write a superposition as “0” + “1”)

In practice, electronic circuits are easier to work with than atoms!

Quantum computing 101

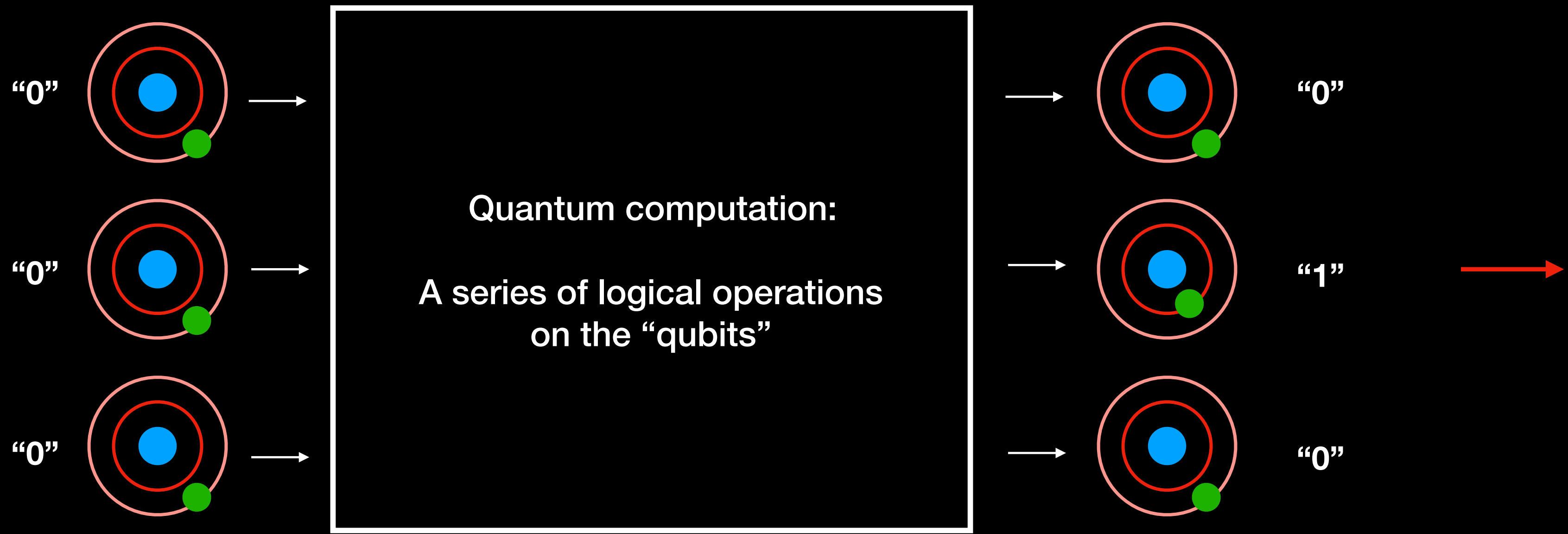
Just like in classical computing, a “quantum program” is ultimately broken down into a series of logical operations such as NOT gates, XOR gates etc. Some of the quantum gates do not have classical analogues, however

A quantum computation proceeds by preparing all the qubits in the “0” state, performing a series of logical operations, and measuring the state of the atoms at the end



Q: What is the probability of a given output configuration, e.g. “010”

Quantum computing 101



According to the rules of QM, we should associate an arrow to every possible output configuration

“000”, “001", “010”, “011”, “100”, “101”, “110”, “111”

For 3 qubits: 8 arrows to keep track of. Each arrow is the result of "adding up” arrows for each possible way that outcome could happen (this is a rather complicated exercise!)

The complexity of quantum computations

Question: How many arrows to keep track of for *n* qubits?

Answer: 2^n

For example: n=300 qubits means we would have to keep track of more than 10^{90} arrows. This is more than the number of atoms in the universe!

For this reason, it is impossible to compute the probability of the outcomes of a quantum computer using a classical (i.e. non-quantum) computer

The quantum computer performs this incredibly complex calculation automatically, thanks to the laws of quantum mechanics. This is the source of the computational power of quantum computers!

(Turning this computational power into useful algorithms is not at all straight forward, and it took a while from the conception of quantum computers until the first important algorithms were developed)

Where are we today?

There are two metrics that determines the power of a quantum computer:

1. **The number of qubits**

2. **The number of logical operations we can perform before noise overwhelms the computation**

IBM and Google have both recently reported results for quantum computers with about 50 qubits

A few tens of logical operations in series can be done before noise becomes a big issue

This is not enough to perform useful algorithms such as breaking cryptography, machine learning, chemistry simulations etc

But it might be enough to do some truly interesting science, because the quantum computers are too hard to simulate classically

Google's recent claim of "Quantum supremacy"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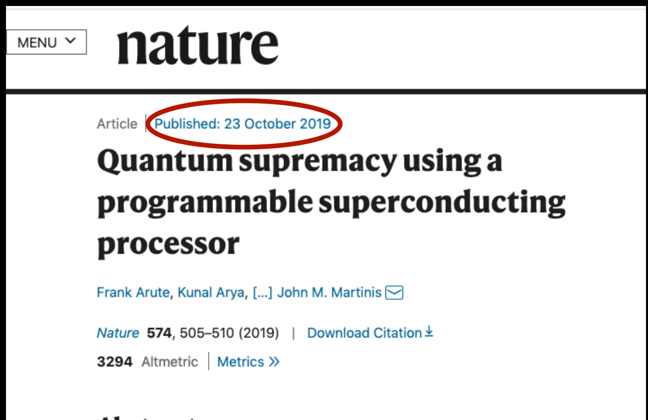
Google claims to have built the first quantum computer that can carry out calculations beyond the ability of today's most powerful supercomputers, a landmark moment that has been hotly anticipated by researchers.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Article Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, […] John M. Martinis

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A paper appeared on the NASA webpages for a brief period in September this year before being taken down again. It finally appeared in published form in the journal *Nature* yesterday (Oct 23)

The paper claims that Google has reached "*quantum computational supremacy*" using a 53 qubit quantum computer

Quantum computational supremacy refers to a quantum computer performing some well-defined computational task that is practically impossible for any conventional supercomputer

It does not matter if the computational task is useful!

The specific computation described in the published paper is very contrived and unlikely to be of any practical use (although you never know!)

Google's recent claim of "Quantum supremacy"

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The claim is, however, being disputed by Google's fiercest competitor in the quantum race: IBM

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IBM Says Google's Quantum Leap Was a Quantum Flop

A paper from Google leaked last month claimed its researchers had achieved "quantum supremacy." Now IBM says Google rigged the test.

The Google/IBM back-and-forth

Google's computation on its 53 qubit quantum computer took about 3 minutes

Google initially claimed that the same calculation on the world's most powerful supercomputer would take 10,000 years (hence the term "quantum supremacy")

But, IBM has now made a counter claim that they could perform the calculation on their supercomputer (which in fact happens to be the world's most powerful) in 2.5 days, by using a smarter algorithm

If IBM is right, there are a couple of things to note:

1. **3 minutes on a 53 qubit quantum computer vs 2.5 days on the *world's most powerful supercomputer* is still really impressive!**

2. **It's all about scaling (remember the 2^n arrows). If Google, say, doubles the number of qubits, it's definitely game over!**

In short, the race is on and the competition is tough… it will likely take some time before any claims of quantum supremacy are widely accepted… and even a longer before *useful* algorithms run on quantum computers