From Niels Bohr to Quantum Computing
- from philosophical struggle to technological revolution

IPAC 2017

Intel® Pentium®

QuadCore processor,

3.5 GHz,

3 GB SDRAM.

395 Euros.

1/1.000.000

x 1.000.000

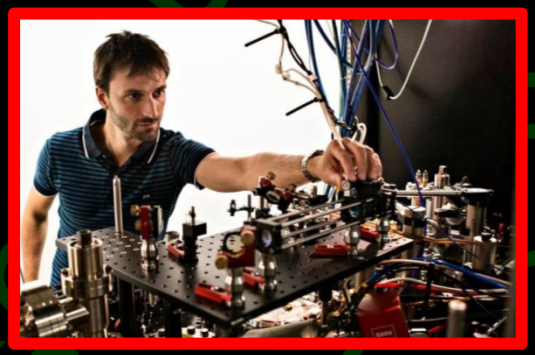
Quantum computer

Processor unknown

1000 Hz is fine, 100 Hz is OK

1000 bit RAM is great !

Buy at **10^9 Euros**

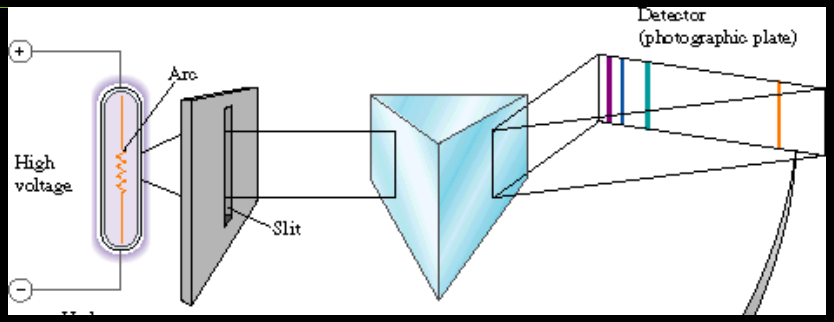


Quantum Physics and Quantum Computing

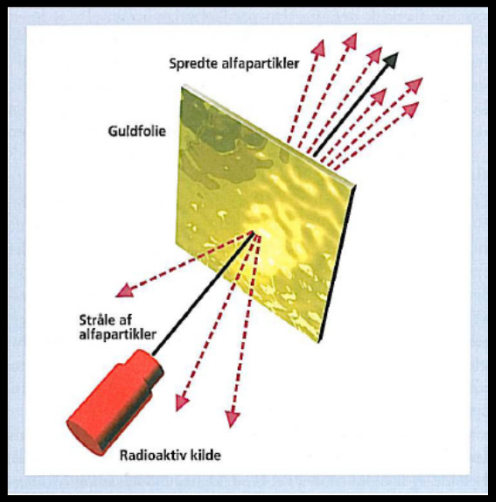
- Some basic, and very strange, properties of quantum mechanics

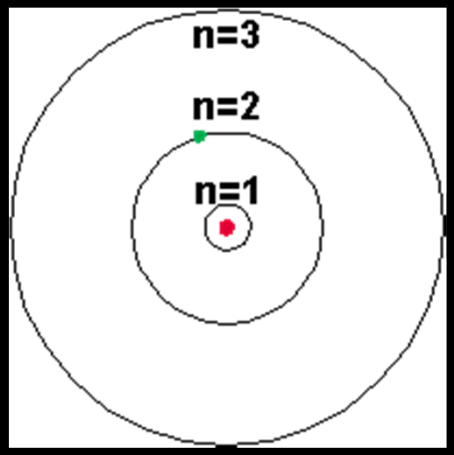
- Quantum computers
  - How they work
  - What they do
  - How we build them

Bohr's model of the atom (1913)



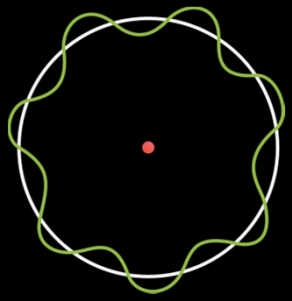
But, it only worked well for Hydrogen





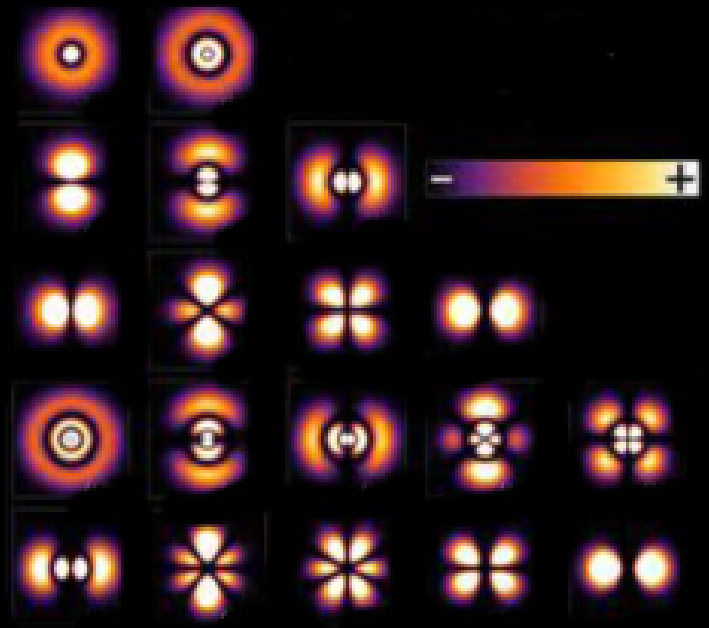
Quantum mechanics

Louis De Broglie:
The electron is a wave

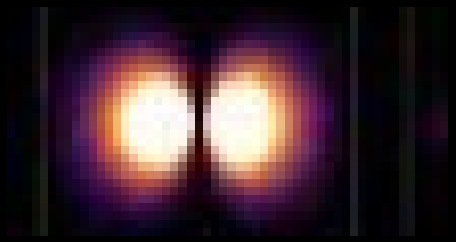


1926: Erwin Schrödinger

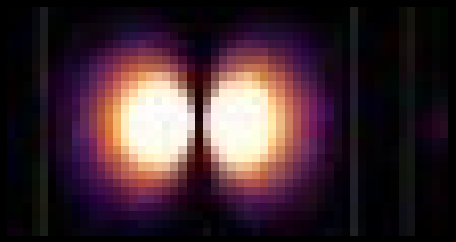
$$i\hbar \frac{d}{dt}\Psi(\vec{r},t) = \left[-\frac{\hbar^2}{2m}\Delta + V(\vec{r})\right]\Psi(\vec{r},t)$$



What does the wave function mean ?



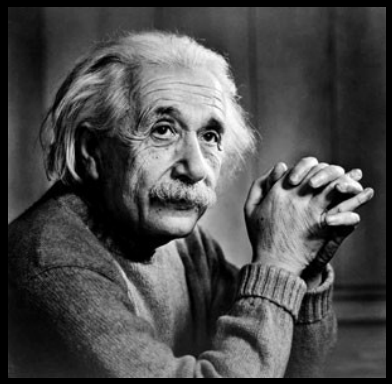
What does the wave function mean ?



$|\psi(x)|^2$ gives the *probability*
… to find the particle at x … .

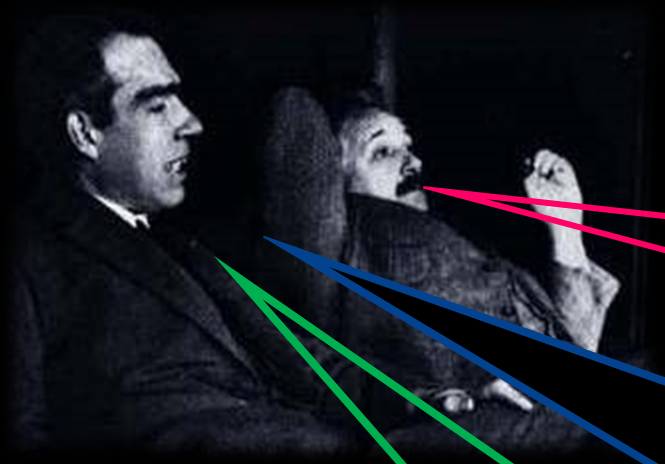
Einstein: ”Does God play dice”

Max Born (1882 -1970)



Is the particle in multiple locations until we detect it ?

Einstein, Podolsky and Rosen (1935)



x_A

→ x_B

”The wave function description does not give a complete description of the physical system.”

”Of course, there is [..] no question of a mechanical disturbance [..] . But, there is essentially the question of an **influence** on the very **condiitons** which define the possible types of **predictions** [...]

[...] these conditions constitute an inherent element of the description of any phenomenon to which the term ”**physical reality**” can be properly attached [...]”.

Quotes on quantum theory

If quantum theory is correct, it signifies the end of physics as a science

Albert Einstein

I do not like it, and I am sorry I ever had anything to do with it.

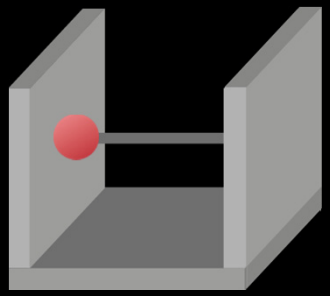
Erwin Schrödinger

But , it works !!!

And, we are ready to apply the craziest effects in the laboratory, and perhaps in future quantum technologies !

How can a small, slow, ”quantum computer” outperform a faster PC or laptop?

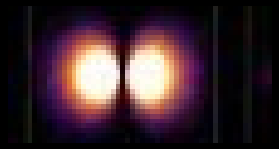
Data bit : 0 *or* 1

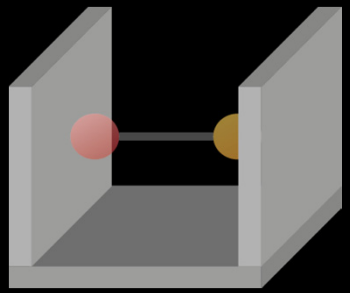


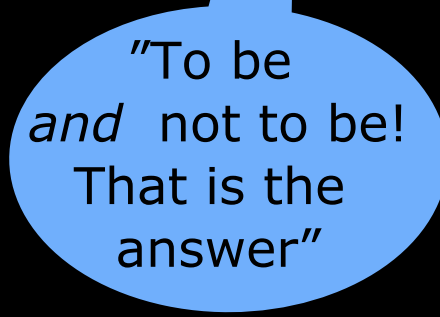
A particle can ”be at different locations at the same time” (wave function)

→ A quantum computer can process two data values at the same time

Quantum bit - ”qubit”: 0 *and* 1







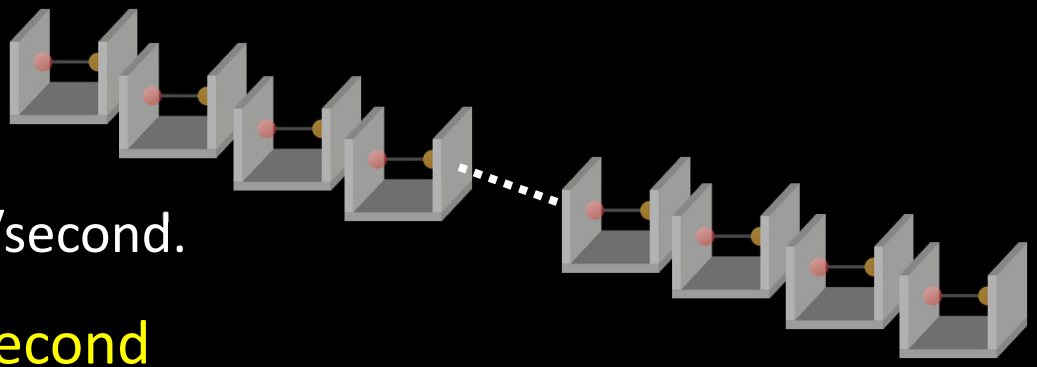
The largest computer vs. the smallest computer in the World

10 million processors

3 billion operations/second (3 GHz)

→ 93 pFlops

= **10^{17}** operations /second



100 quantum bits. One operation/second.

→ 2^{100} ~**10^{30}** operations/second

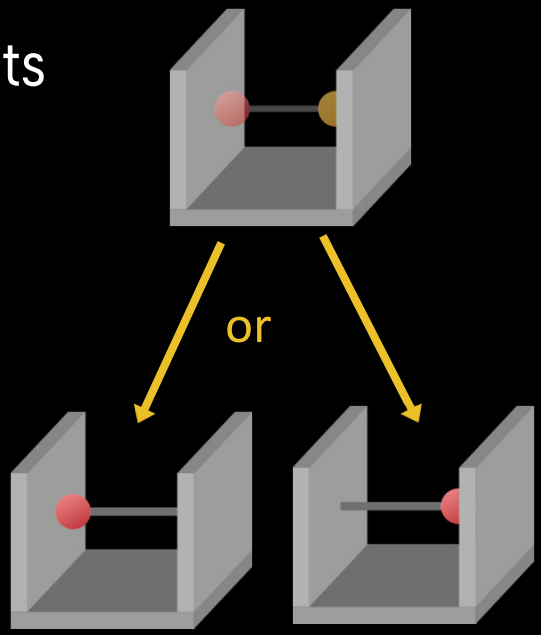
The quantum computer

Uses that bits can have values 0 and 1 at the same time.

Performs same calculations as classical computer :

- Same basic operations (gates) on the bits,
- Several initial values propagate
  in parallel towards several final results

Problem: "God plays dice"



The quantum algorithms

The quantum computer permits evaluation of a function on all inputs in one execution, but it does not permit read-out of all values!

Peter Shor (1994): A hard problem with only one correct answer

$2257 = ? \cdot ?$

$2257 = 37 \cdot 61$

For large numbers: $N = x \cdot y$, find x and y.

If N is a 200 digit number, the world's computer power combined will not factor N in a million years.

And much more ...

Quantum computers can

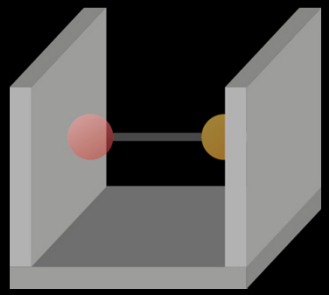
- Factor numbers (break codes)
- Search data-bases
- Simulate quantum spin models
- Search energy landscapes
- Simulate lattice QED/QCD
- Perform fast machine learning
- Solve problems in quantum chemistry
- ...

Quantum gates

One-bit gates

NOT: 0 $\leftrightarrow$ 1

”without looking”.



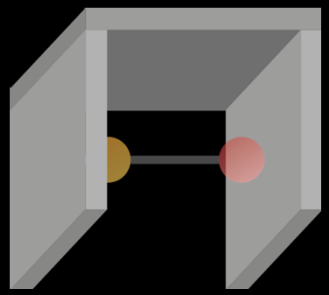
Must maintain ”0 *and* 1”

Quantum gates

One-bit gates

NOT: 0 $\leftrightarrow$ 1

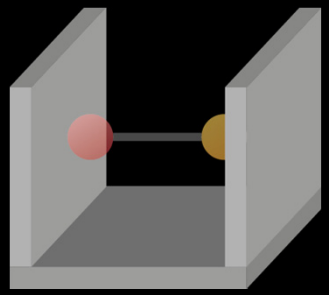
”without looking”.



Must maintain ”0 *and* 1”

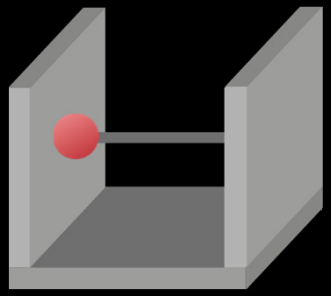
Quantum gates

One-bit gates
NOT: 0 ↔ 1
”without looking”.

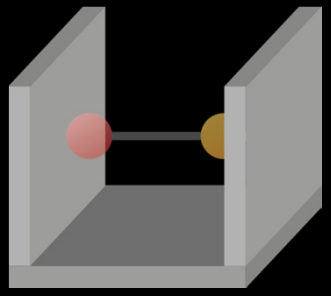


Must maintain ”0 *and* 1”

Two-bit gate
C-NOT
”without looking”.



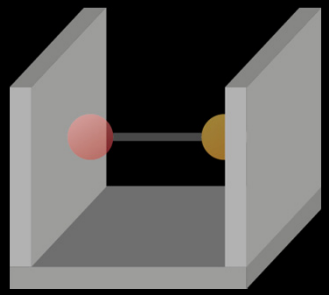
”Control”: 0



”Target”: no change

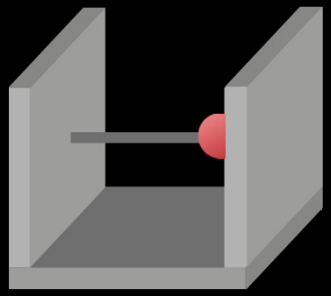
Quantum gates

One-bit gates
NOT: 0 ↔ 1
”without looking”.

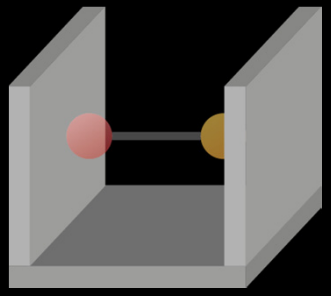


Must maintain ”0 *and* 1”

Two-bit gate
C-NOT
”without looking”.



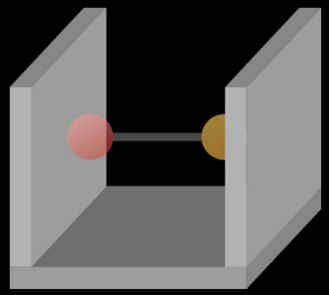
”Control”: 1



”Target”: 0 ↔ 1

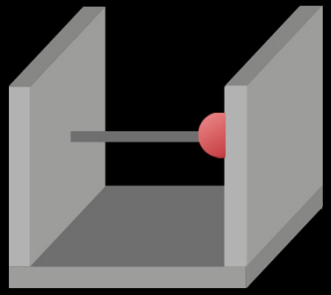
Quantum gates

One-bit gates
NOT: 0 ↔ 1
”without looking”.

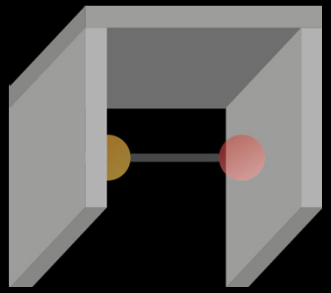


Must maintain ”0 *and* 1”

Two-bit gate
C-NOT
”without looking”.



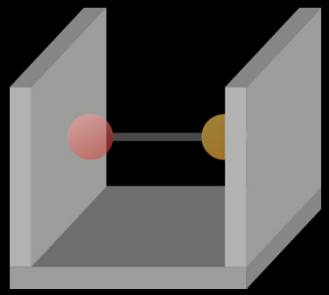
”Control”: 1



”Target”: 0 ↔ 1

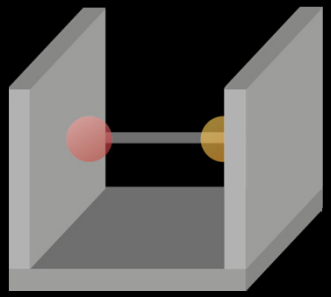
Quantum gates

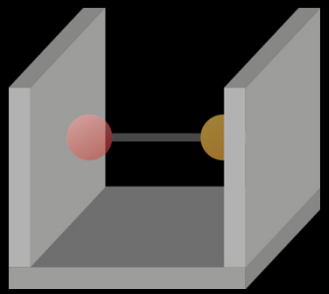
One-bit gates
NOT: 0 ↔ 1
”without looking”.



Must maintain ”0 *and* 1”

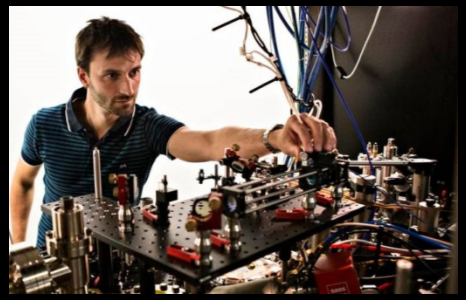
Two-bit gate
C-NOT
”without looking”.

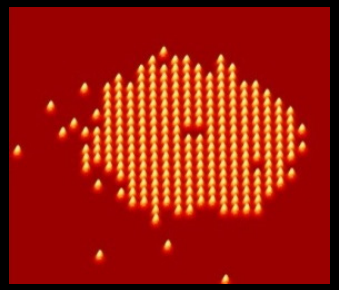


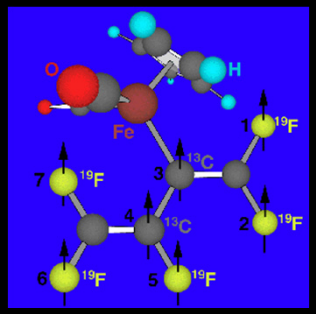


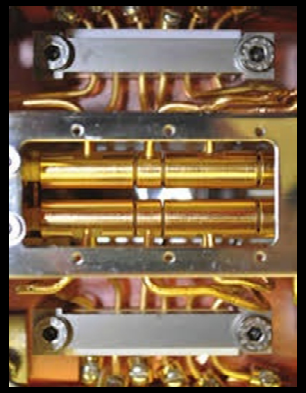
”Control”: 0 and 1 ”Target”: ?

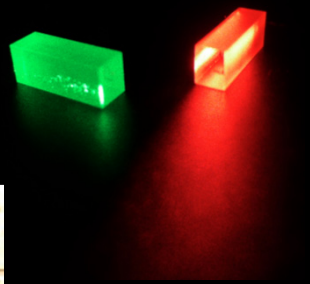
Competing technologies

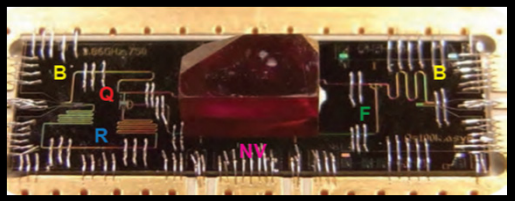


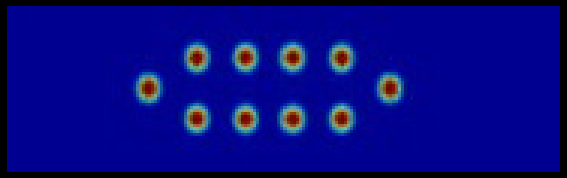










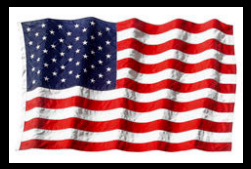


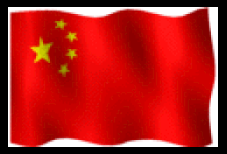
Today: 10-20 good bits, 100-1000 bad bits

2018: 50 good bits (> 42)

Who will build it?

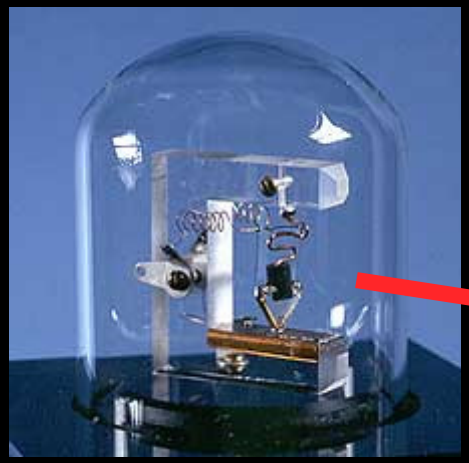
Google
IBM
Microsoft
Intel
AliBaba
D-Wave
BlackBerry (Mike Lazaridis)
…





EuropeanUnion :
Horizon 2020
Quantum Technology Flagship
1 billion euros

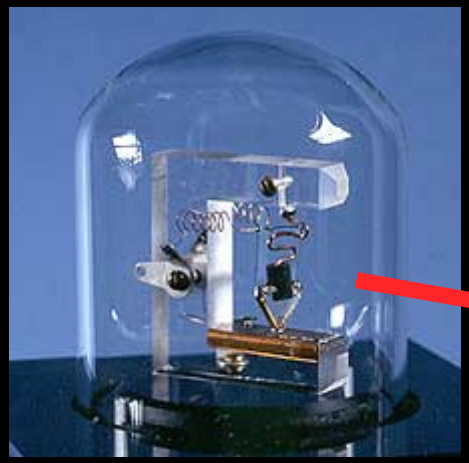
The long and winding path from basic research to application



First transistor (1947)

1 billion transistors in a single chip

The long and winding path from basic research to application



First transistor (1947)

First commercial application of one single transistor

Hearing aids

1 billion transistors in a single chip

And if we fail …

Niels Bohr
(on Quantum Mechanics):

” … if we should one day wake up, and realize that it had all been only a dream, then I am absolutely convinced that we would still have learned something !”