Quantum Computing & Cryptography

Christian Schaffner

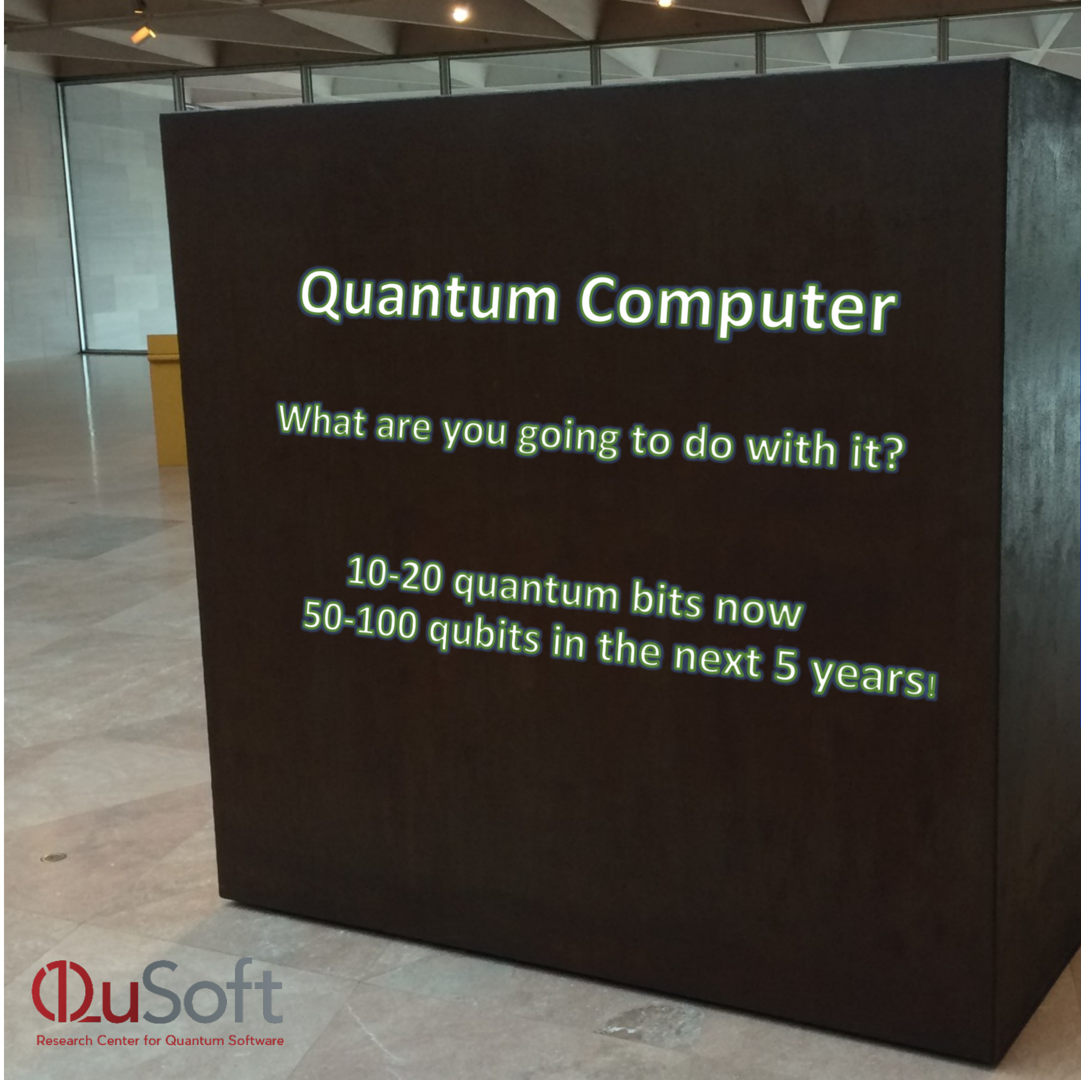
QuSoft Research Center for Quantum Software

Institute for Logic, Language and Computation (ILLC)
University of Amsterdam

Landing Festival Berlin, 3 April 2019

Nederlandse Organisatie voor Wetenschappelijk Onderzoek

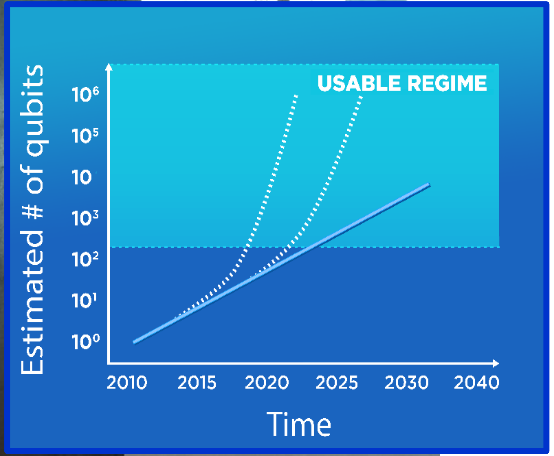
A little thought experiment...



Quantum Computer

What are you going to do with it?

10-20 quantum bits now
50-100 qubits in the next 5 years!



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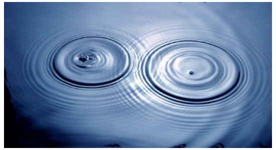
QUANTUM OF SOLACE
007
OUCH®
Healing 101
How t al pain
ith quant ower

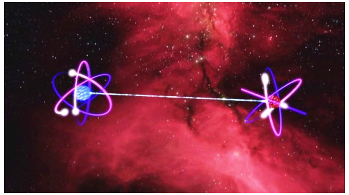
Quantum Physics

1. Superposition:
   - Of different states

2. Interference:
   - Of states



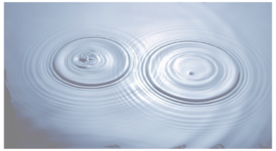
3. Entanglement:
   - Of two or more physical systems



Quantum Physics

1. Superposition:
   - Of different states

2. Interference:
   - Of states



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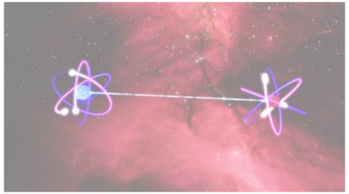
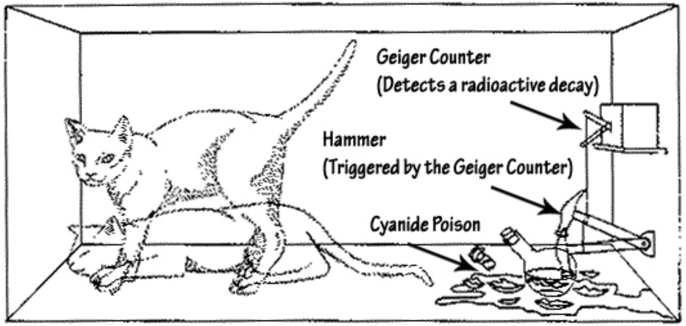


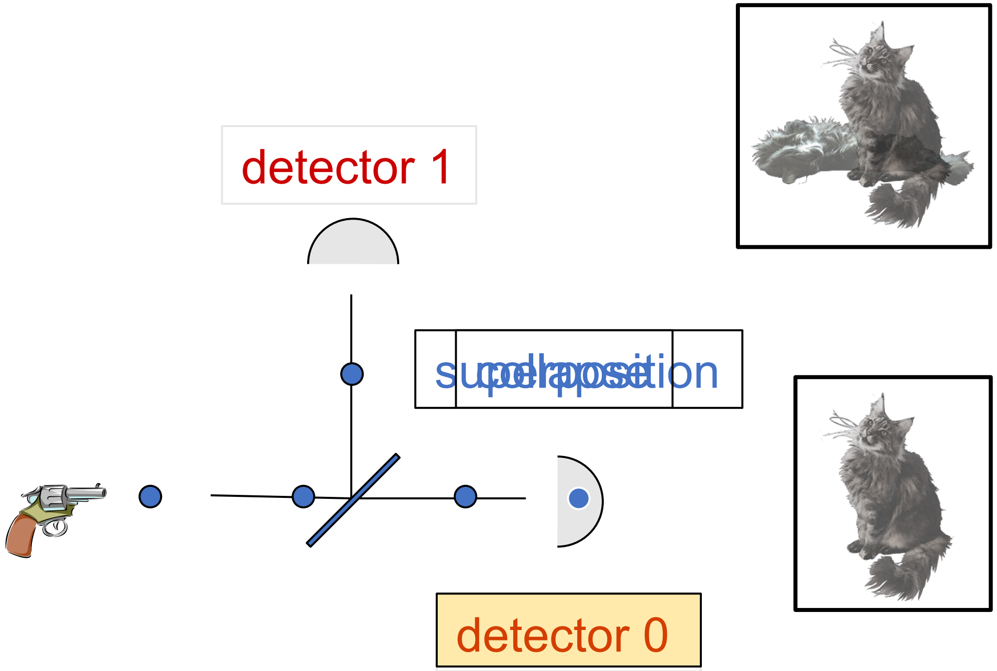
Superposition

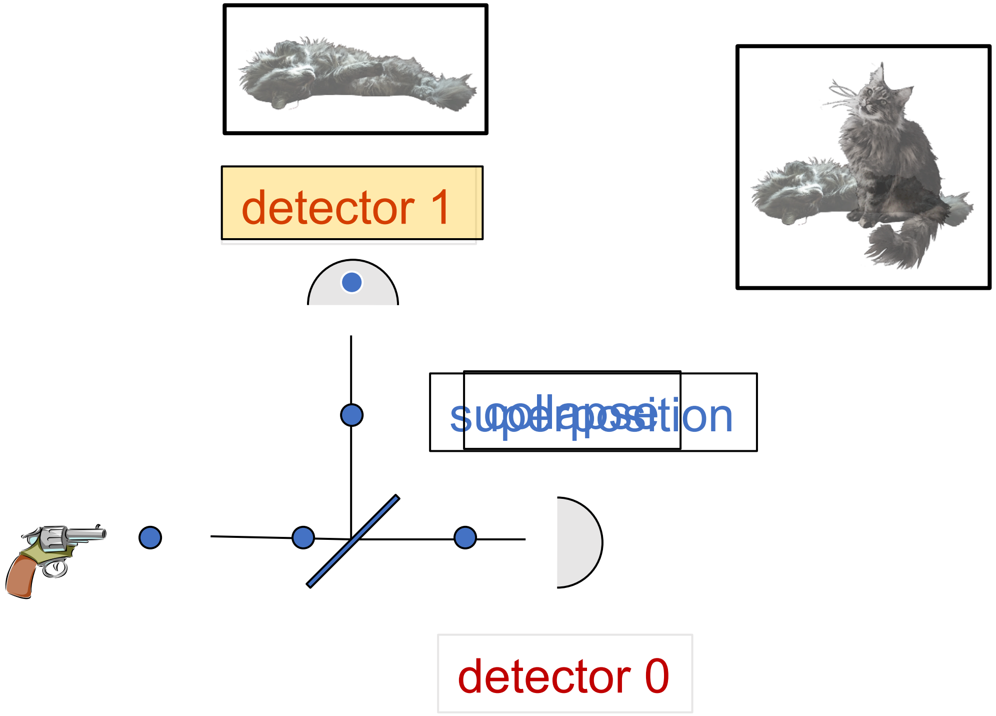
- An object in different states simultaneously:
  - A photon can be at two positions at the same time
  - Schrödinger’s cat: dead and alive

- Experimentally verified:
  - Small systems, such as photons
  - Bigger systems, molecules…


Geiger Counter
(Detects a radioactive decay)
Hammer
(Triggered by the Geiger Counter)
Cyanide Poison

Superposition: An experiment


detector 1
superposition
collapse
detector 0



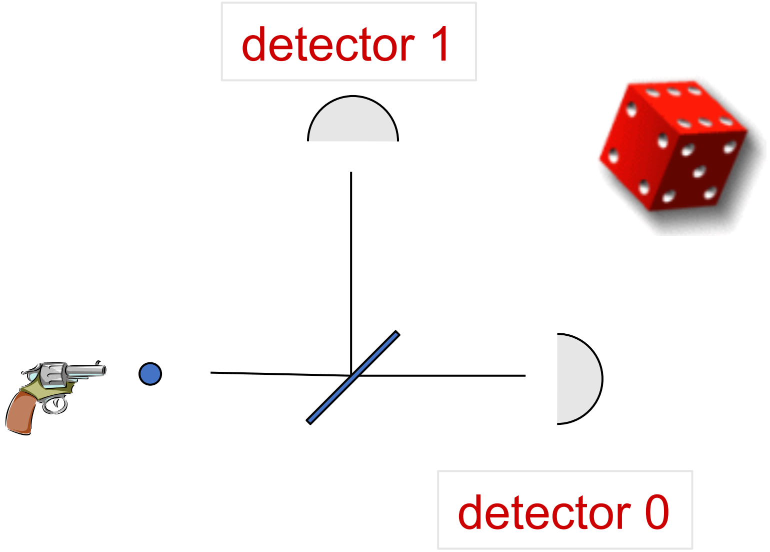
detector 1

superposition

collapse

detector 0

50% detector 0 clicks
50% detector 1 clicks



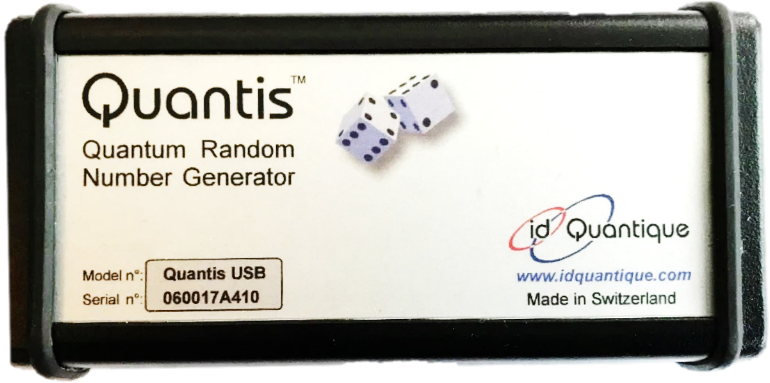
detector 1

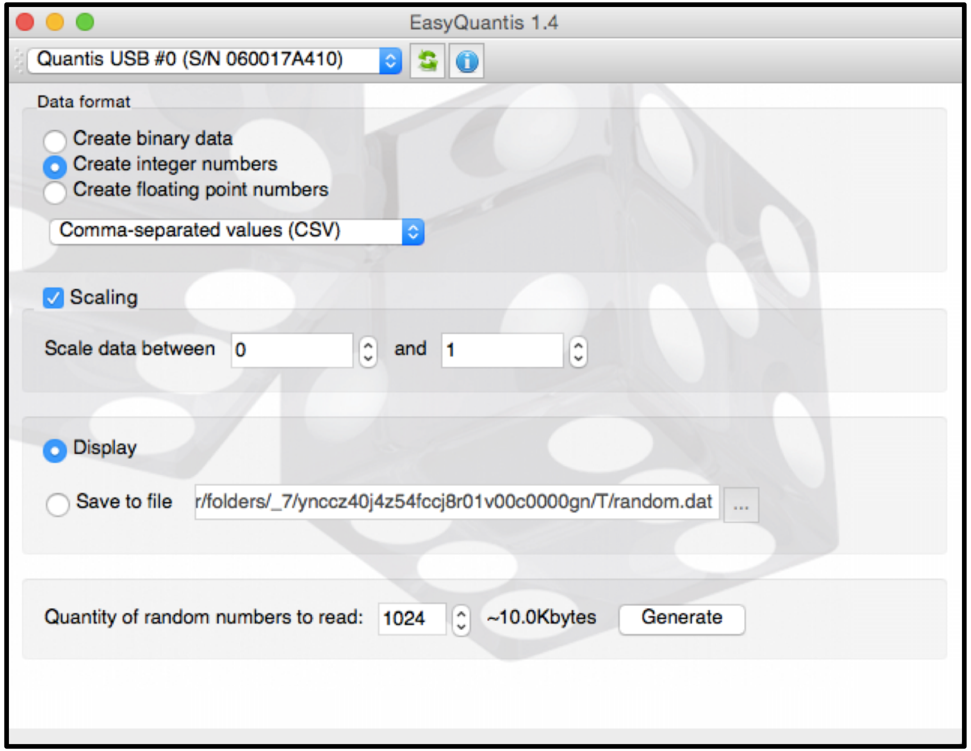
detector 0

Random Number Generator

Swiss company:

id Quantique





EasyQuantis 1.4

Quantis USB #0 (S/N 060017A410)

Data format

○ Create binary data

● Create integer numbers

○ Create floating point numbers

Comma-separated values (CSV)

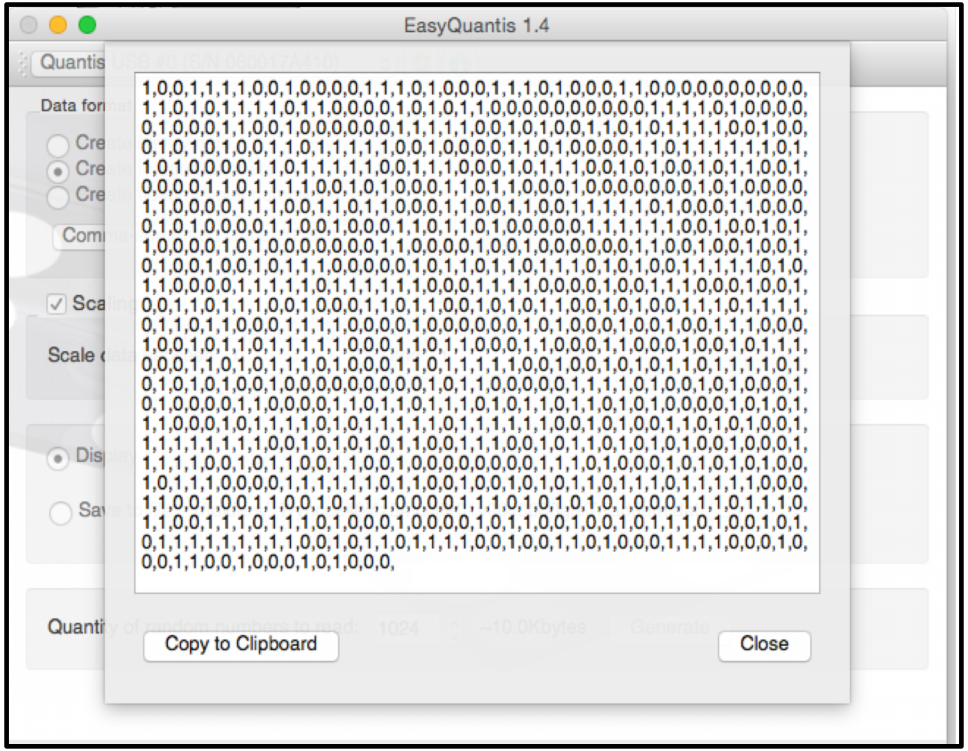
☑ Scaling

Scale data between 0 and 1

● Display

○ Save to file r/folders/_7/ynccz40j4z54fccj8r01v00c0000gn/T/random.dat

Quantity of random numbers to read: 1024 ~10.0Kbytes


EasyQuantis 1.4
Quantis USB #0 (S/N 060017A410)
Data format
Cre
Cre
Cre
Comma
☑ Scaling
Scale data
Display
Save
Quantity of random numbers to read: 1024 ~10.0Kbytes Generate
Copy to Clipboard
Close

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1,0,0,1,1,1,1,0,0,1,0,0,0,0,1,1,1,0,1,0,0,0,1,1,1,0,1,0,0,0,1,1,0,0,0,0,0,0,0,0,0,
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0,0,1,1,0,0,1,0,0,0,1,0,1,0,0,0,
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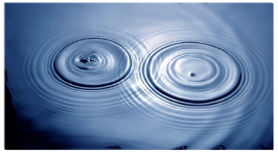
Quantum Physics

1. Superposition:
   - Of different states
   - Observation: collapse of the superposition

2. Interference
   - Of an object in superposition



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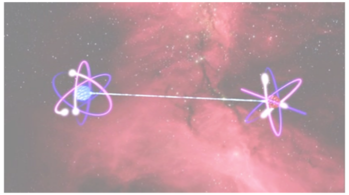
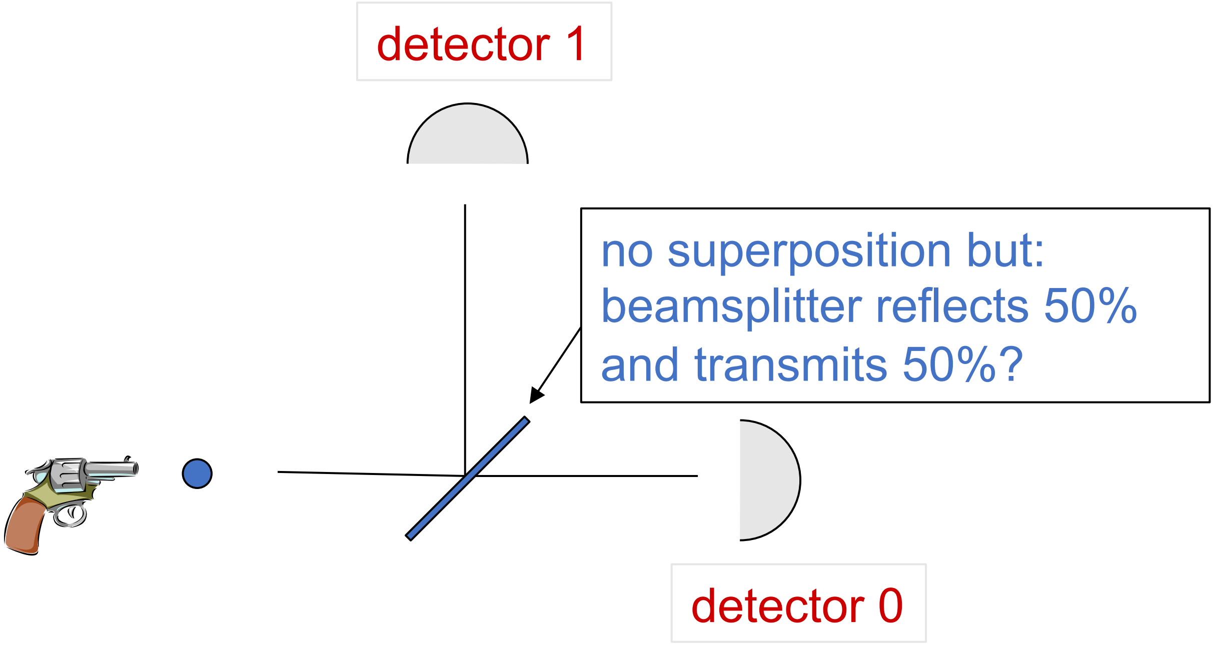
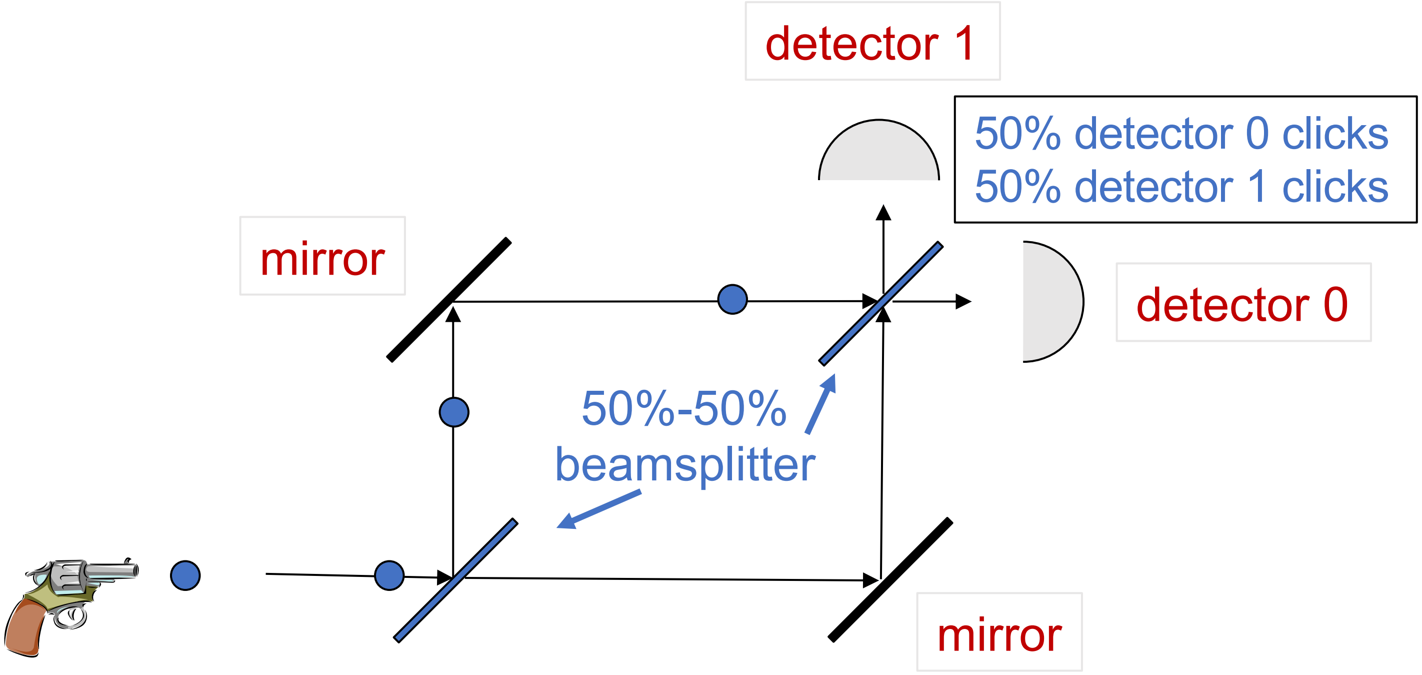




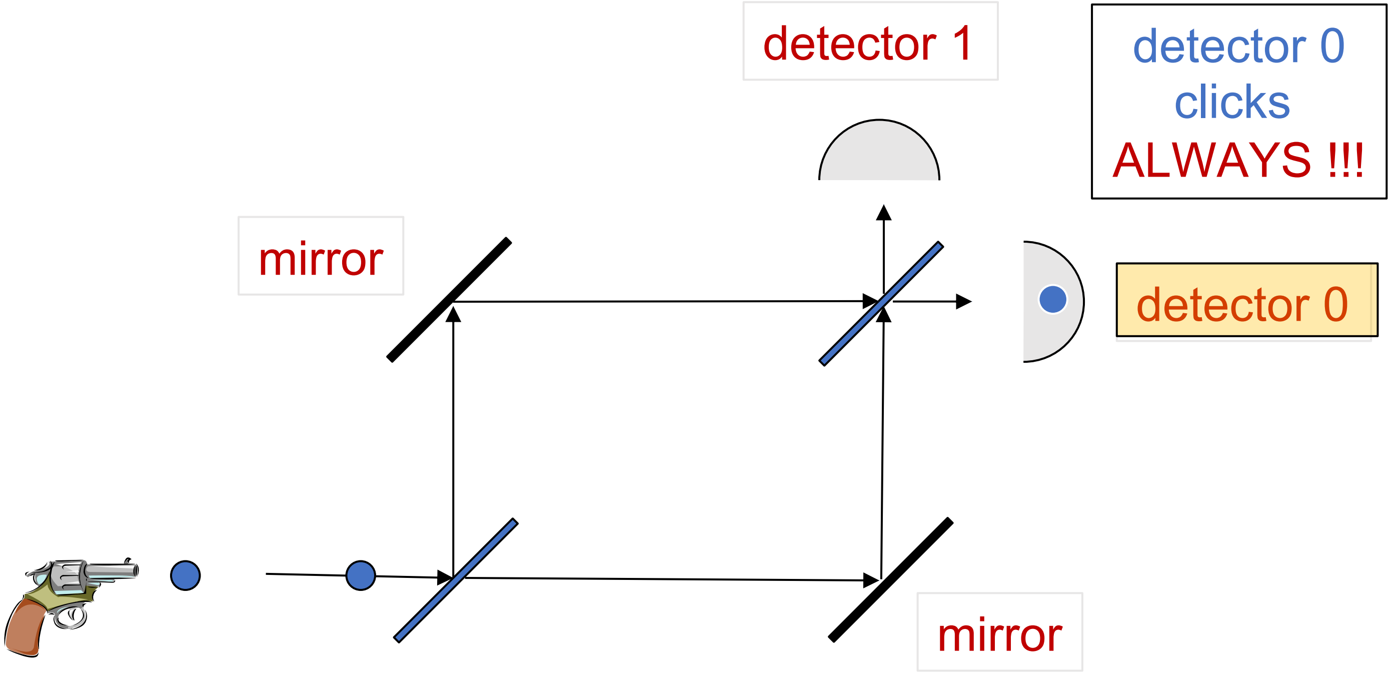
no superposition but: beamsplitter reflects 50% and transmits 50%?

Mach-Zehnder interferometer



classical reasoning

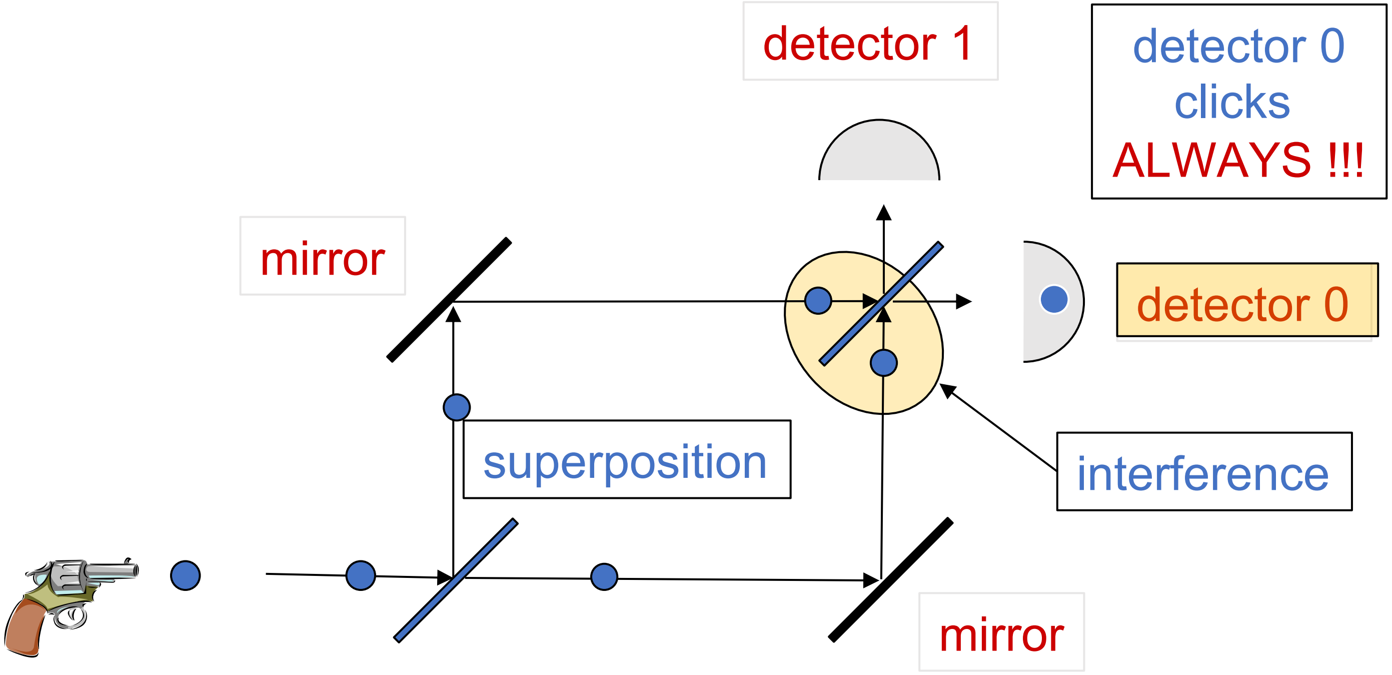
Mach-Zehnder interferometer



detector 0 clicks ALWAYS !!!

When you perform the experiment

Try it yourself: http://quantumgame.io/



According to quantum mechanics

Quantum Physics

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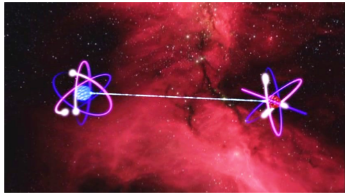
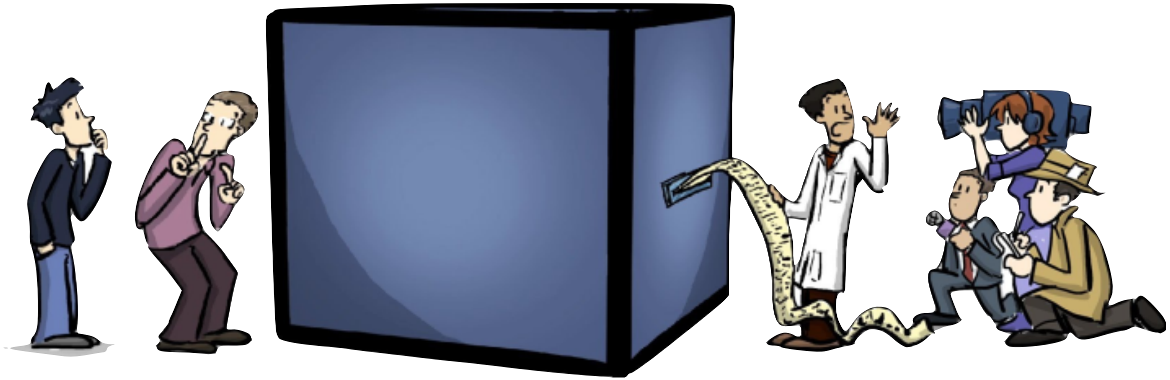
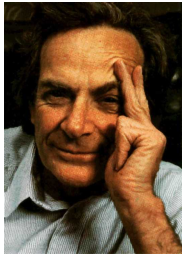
3. Entanglement:
   - Of two or more physical systems



Quantum Physics
+ Computer Science = A Quantum COMPUTER





Feynman 1981

Deutsch 1985

Video: [Quantum Computers Animated]

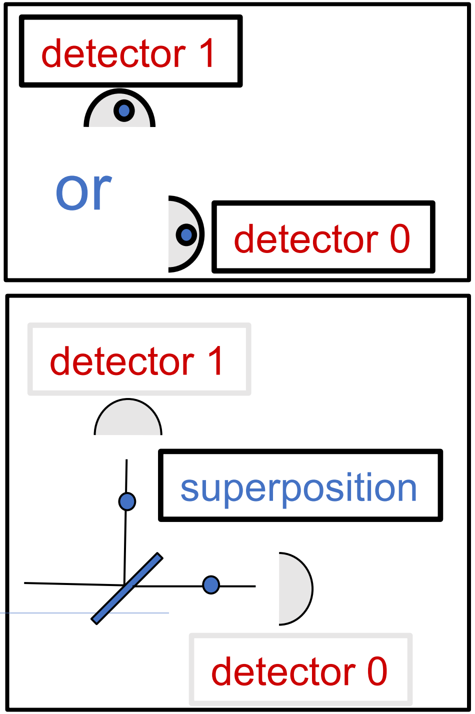
Quantum Bit (QuBit)

- Classical bit:

  0 or 1

- Quantum bit:

  superposition of **0 and 1**



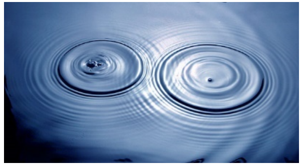
Research Center for Quantum Software

More Qubits

- 1 qubit superposition of 2 states
- 2 qubits superposition of 4 states
- 3 qubits superposition of 8 states
- 4 qubits superposition of 16 states
- 5 qubits superposition of 32 states
- 6 qubits superposition of 64 states
- 300 qubits superposition of 2^{300} states

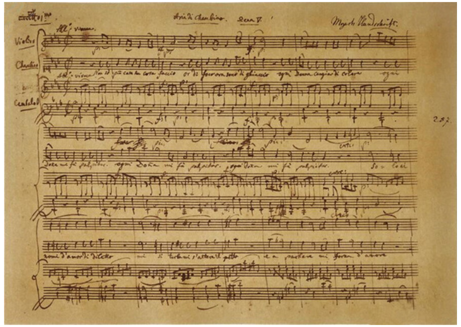
Quantum Software: Fundamentally Different

- Qubit: superposition of 0 and 1
- 300 qubits: astronomical amount of parallel computation
- How to get the answer out??
  - Measuring destroys computation!!
- Quantum Program
  - Use interference to cancel undesired computations
- Does not always work!

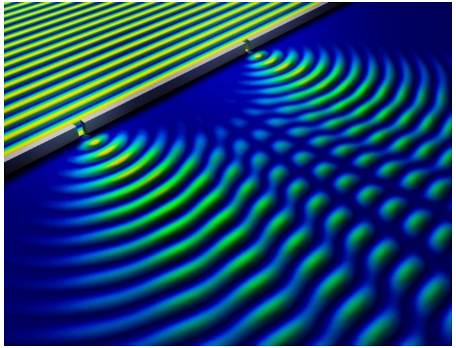


Our focus: how can we optimally use the extra power?

Quantum Programming is like Composing



- Music
  - Sound waves interfere
  - Composer creates ‘beautiful’ interference of sound waves

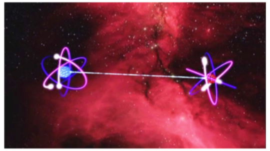


- Quantum Computer
  - Qubits in superposition interfere
  - Quantum programmer ensures useful interference of qubit states

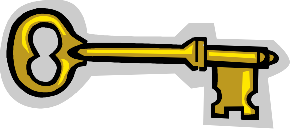
What can you do with it?

- Simulation of nature
  - Chemistry, material design, new medicines..

- Efficient communication
  - Quantum internet, entanglement etc.



- Factorizing big numbers [Shor]
  - Breaks frequently used cryptography

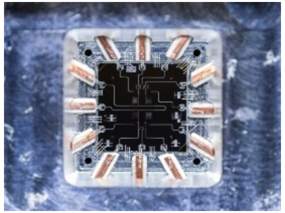


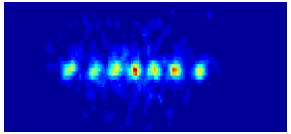
- Quantum cryptography [Bennett-Brassard-Ekert]
  - Cryptography using quantum communication

- ??????

Progress In Building Qubits

- Many groups worldwide progress with building qubits
- Solid state:
  - 50 solid-state qubits IBM
  - 49 Intel
  - 50 Google → 72
  - Fairly stable
- Trapped ions:
  - 11 qubits Monroe
- D-Wave:
  - 2048 qubits (not very stable)





Isolation vs Control

https://quantumcomputingreport.com/

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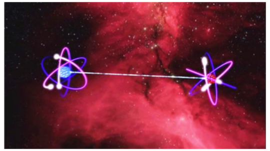
- Efficient communication
  - Quantum internet, entanglement etc.



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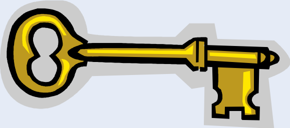
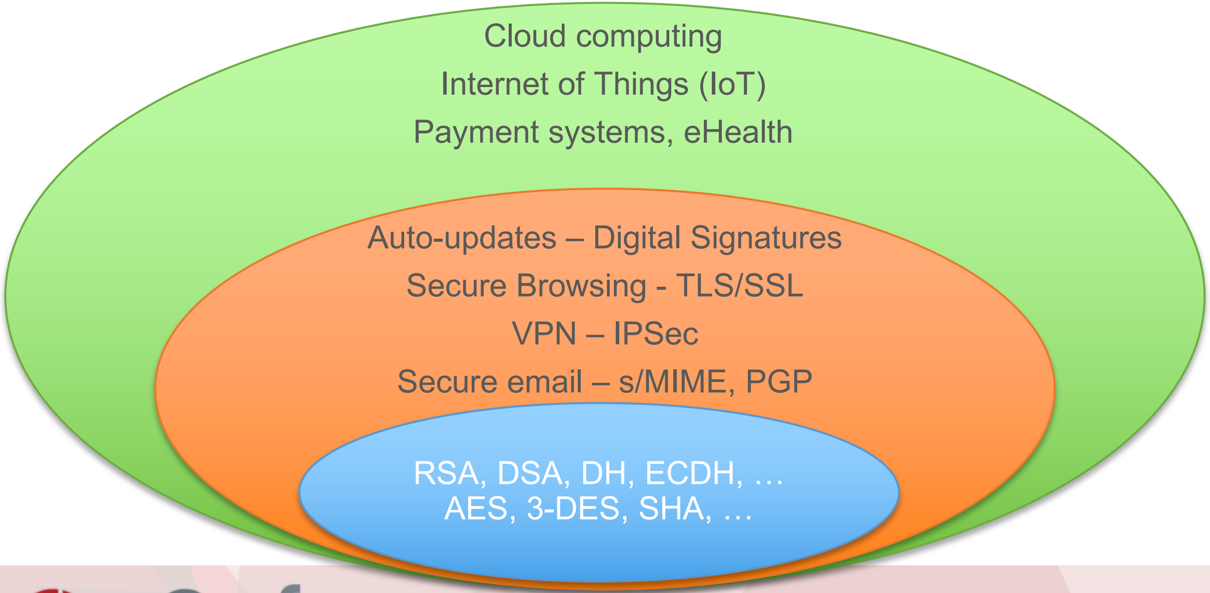


- Quantum cryptography [Bennett-Brassard-Ekert]
  - Cryptography using quantum communication

- ??????

Cyber Security

"Cyber Security provides security, safety and privacy solutions that are vital for our economy including but not limited to critical infrastructures, smart cities, cloud computing, online services and e-government."



Cloud computing

Internet of Things (IoT)

Payment systems, eHealth

Auto-updates – Digital Signatures

Secure Browsing - TLS/SSL

VPN – IPSec

Secure email – s/MIME, PGP

RSA, DSA, DH, ECDH, …
AES, 3-DES, SHA, …

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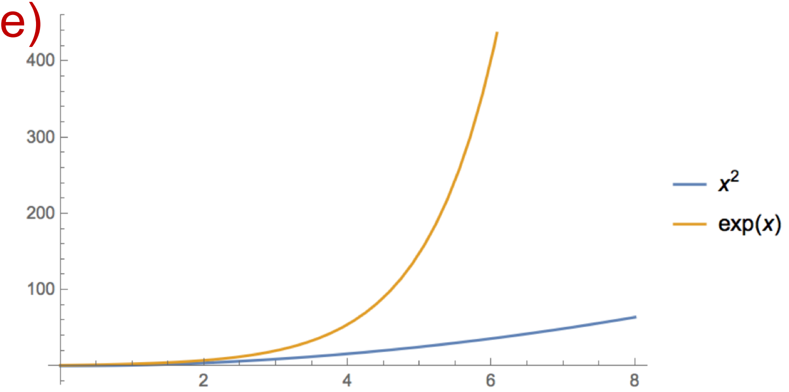
based on slides by Michele Mosca

Quantum Algorithm for Factorization

- Peter Shor 1994: efficient quantum algorithm for factoring integer numbers
- 15 = 3 * 5
- 27 =
- 31 =
- 57 =
- 91 =
- 173 =
- RSA-100 = 1522605027922533360535618378132637429718068114961380688657908494580122963258952897654000350692006139

Quantum Computer Breaks Public-Key Crypto

- Peter Shor 1994: efficient quantum algorithm for factoring integer numbers
- For a 600-digit number (RSA-2048)
  - Classical: age of universe (exponential time)
  - Quantum: few minutes (polynomial time)
- Consequence: Large enough quantum computers break all currently used public-key cryptosystems!!!



Current Cryptography Under Quantum Attack

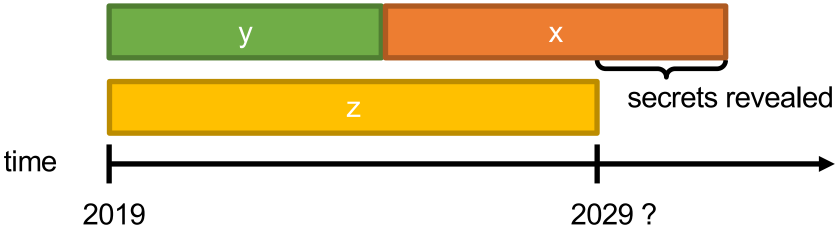
Security level systems	Conventional attacks	Quantum attacks
Symmetric-key encryption (AES-256)	256 bits of security	128 bits
Hash functions (SHA3-256)	128 bits	85 bits
Public-key crypto (key exchange, digital signatures, encryption) (RSA-2048, ECC-256)	112 bits	~ 0 bits

Products, services, businesses relying on security either stop functioning or do not provide expected levels of security!

When Do We Need To Worry?

Depends on:

- How long do you need to keep your secrets secure? (x years)
- How much time will it take to re-tool the existing infrastructure? (y years)
- How long will it take for a large-scale quantum computer to be built? (z years)
- Theorem (Mosca): If x + y > z, then worry.



- If x > z or y > z, you are in big trouble!

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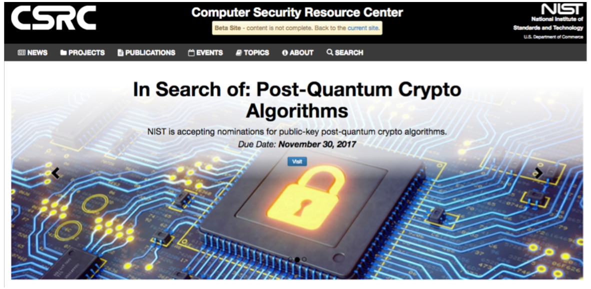
slide by Michele Mosca

Conventional Quantum-Safe Cryptography

- **Wanted**: new assumptions to replace factoring and discrete logarithms in order to build conventional public-key cryptography


CSRC
Computer Security Resource Center
Beta Site - content is not complete. Back to the current site.
NIST
National Institute of Standards and Technology
U.S. Department of Commerce
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PROJECTS
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EVENTS
TOPICS
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In Search of: Post-Quantum Crypto Algorithms

NIST is accepting nominations for public-key post-quantum crypto algorithms.

Due Date: ***November 30, 2017***

https://csrc.nist.gov/Projects/Post-Quantum-Cryptography

- NIST “competition”: 82 submissions (23 signature, 59 encryption schemes)
- Aug 2019: Second-round workshop in California
- Expected: 3-5 years of crypto-analysis
- New standards, world-wide adoption

The Future is Quantum: Governments

- QuTech in Delft, NL: €135 million
- €18.8 Mio for 10 years: Quantum Software Consortium

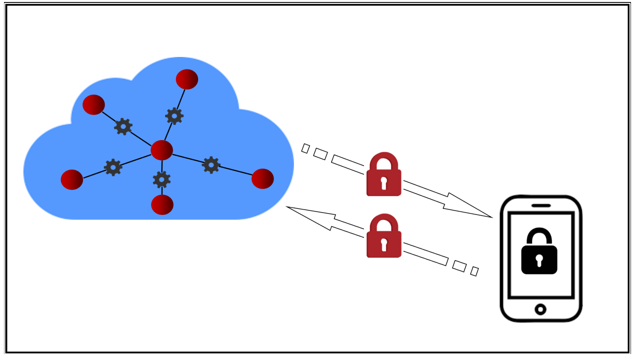
- Germany: €650 million for quantum technologies
- UK: £235 million five-year in quantum computing
- Sweden: €100 million for 10 years for WACQT
- EU Flagship: €1 billion and a duration of 10 years

- US: $1.2 billion National Quantum Initiative Act
- China: $1 billion initial funding for National Laboratory for Quantum Information Sciences
- Canada, Australia, Singapore, …

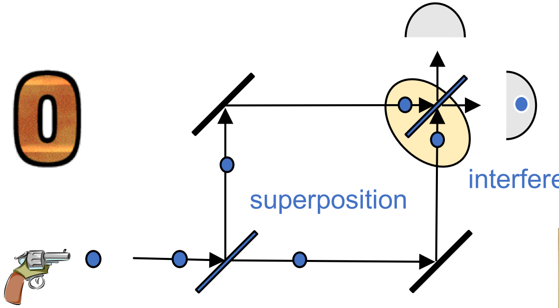
https://sciencebusiness.net/news/eu-runs-catch-governments-pledge-more-cash-quantum-computing

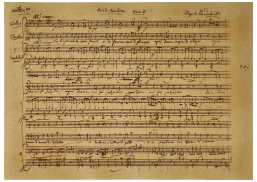
The Future is Quantum: Business

- Quantum networks
- Quantum cloud



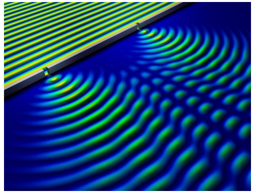
Y. Dulek, C. Schaffner, and F. Speelman, arXiv:1603.09717
Quantum homomorphic encryption for polynomial-sized circuits

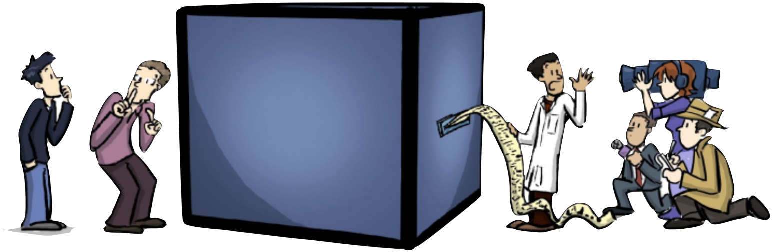


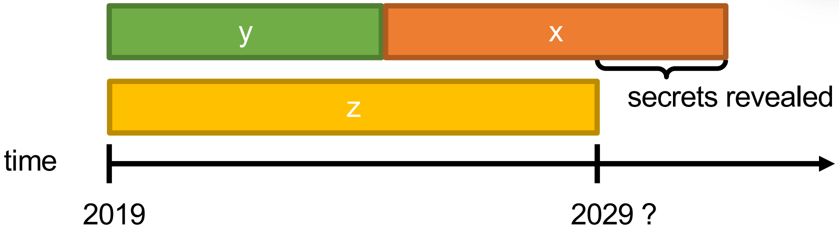


Summary

Security systems	Standard attacks	Quantum attacks
Symmetric	256 bits of security	128 bits
Hash	128 bits	85 bits
Public-key	112 bits	~ 0 bits







Thank you for your attention!

“About your cat Mister Schrödinger…
I’ve got good **and** bad news.”

Get in touch: schaffner@qusoft.org

QuSoft
Research Center for Quantum Software