Quantum Computers vs. Computers Security

@veorq — http://aumasson.jp

DEF CON 23

LAS VEGAS

Schrodinger equation

Entanglement

Bell states

EPR pairs

Wave functions

Uncertainty principle

Tensor products

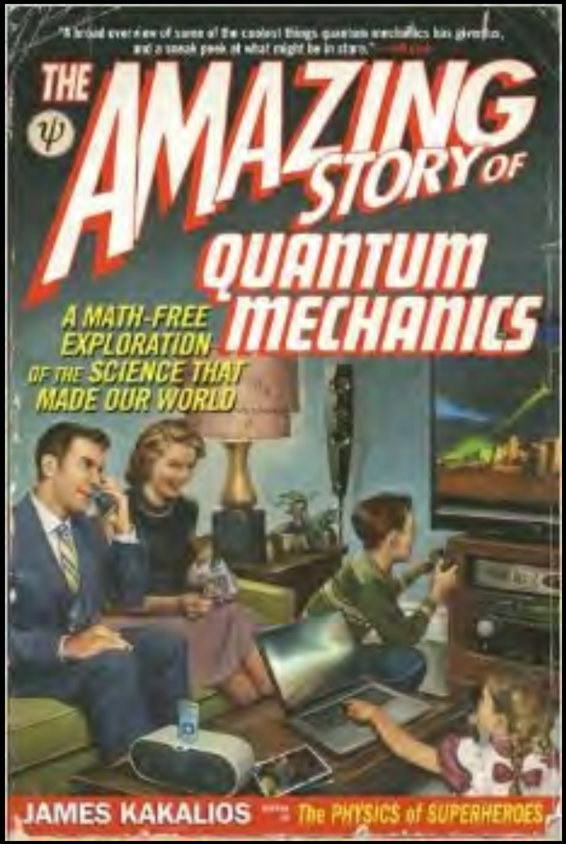
Unitary matrices

Hilbert spaces

Nobody understands this stuff, and you don't need it to understand quantum computing

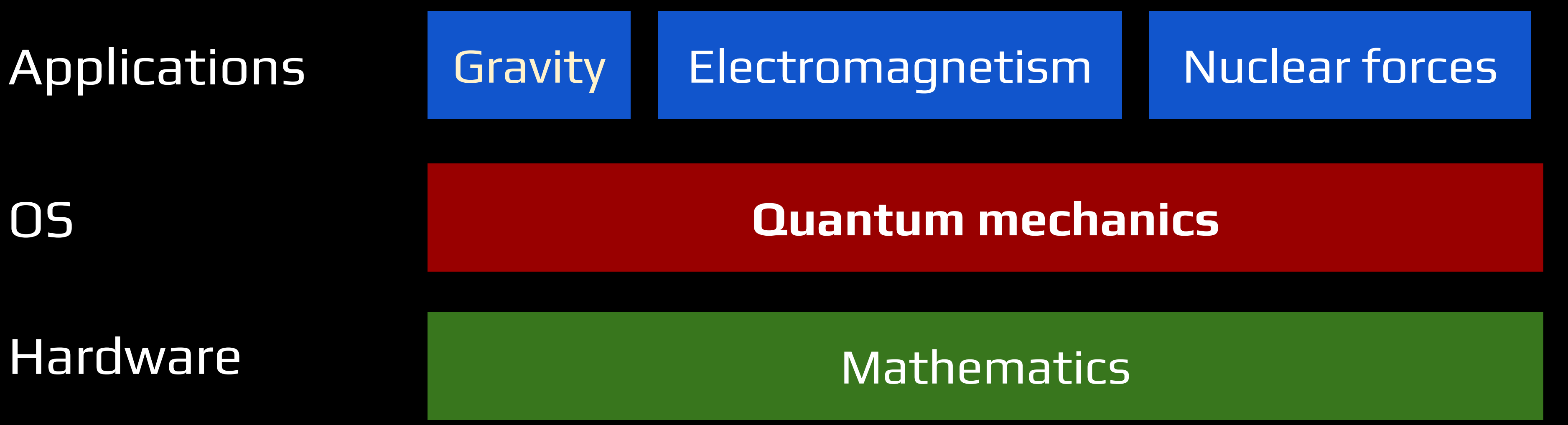
1. QC 101
2. In practice
3. Breaking crypto
4. Post-quantum crypto
5. Quantum key distribution
6. Quantum copy protection
7. Quantum machine learning
8. Conclusions

1. QC 101


THE AMAZING STORY OF QUANTUM MECHANICS
A MATH-FREE EXPLORATION OF THE SCIENCE THAT MADE OUR WORLD
JAMES KAKALIOS
The PHYSICS of SUPERHEROES

Quantum mechanics

Nature’s operating system



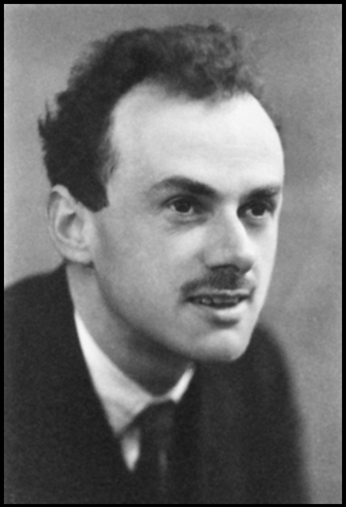
Quantum mechanics

Particles in the universe behaves **randomly**

Their probabilities can be **negative**

"Negative energies and probabilities should not be considered as nonsense. They are well-defined concepts mathematically, like a negative of money."

—Paul Dirac, 1942



Quantum bit (qubit)

$$\alpha\,|0\rangle + \beta\,|1\rangle$$

When observed

- 0 with probability α^2
- 1 with probability β^2

Once observed, stays either 0 or 1 forever

Quantum byte

$$\alpha_{0x00} |0x00\rangle + \ldots + \alpha_{0xfe} |0xfe\rangle + \alpha_{0xff} |0xff\rangle$$

Again, the sum of probabilities α^2 equals 1

The α's are called **amplitudes**

Generalizes to 32- or 64-bit quantum words

Quantum computer

Set of **quantum registers** (bits/bytes/words)

Quantum assembly instructions:

- Transform the probabilities of the register
- Probabilities should still sum to 1
- Linear math transforms (matrix products)

A program ends with a measurement

Quantum computer simulators

The killer app

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Impossible with a classical computer

Possible with a quantum computer!

QC vs. hard problems

You heard about **NP-complete** problems?

- SAT, scheduling, Candy Crush, etc.
- Solution hard to find, but easy to verify

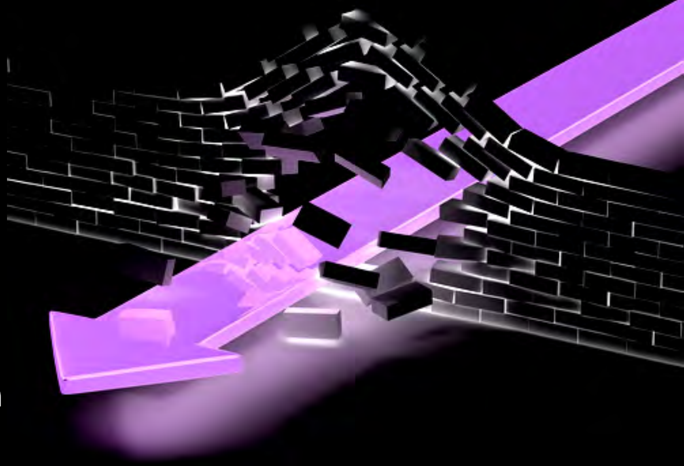
QC **does not** solve NP-complete problems!

BQP (quantum)

NP
(hard)

P
(easy)

Quantum speedup



Make the impossible possible

Example: **Factoring integers**

Hard classically (exponential-ish)

Easy with a quantum computer!

Obvious application: **break RSA!**

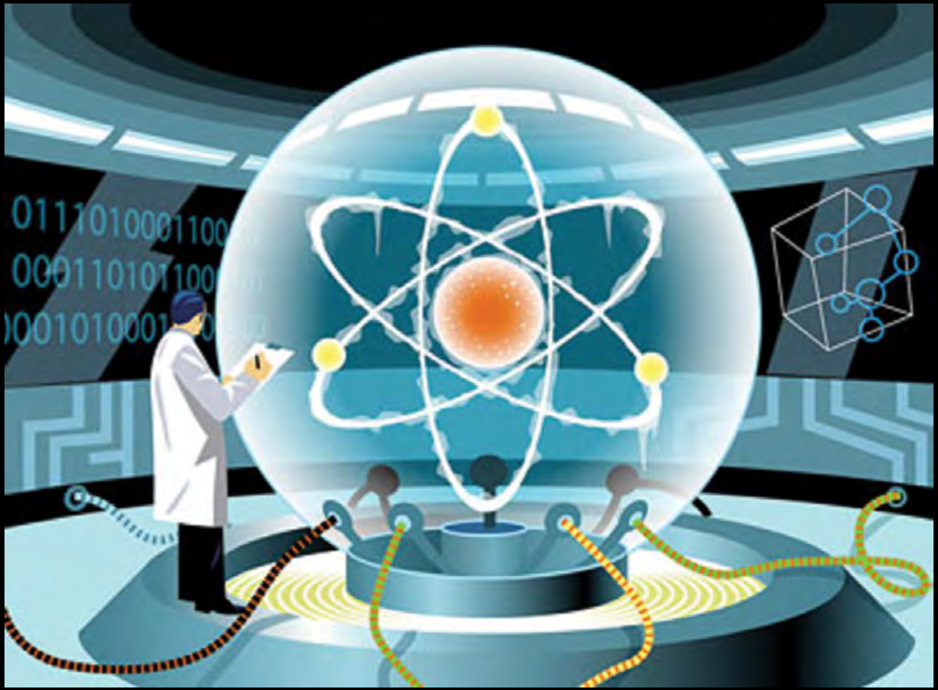
Quantum parallelism

“Qubits encode all values at the same time!”

Caveat: you can only **observe one** result

Different observations in different worlds

2. In practice



Factoring experiments

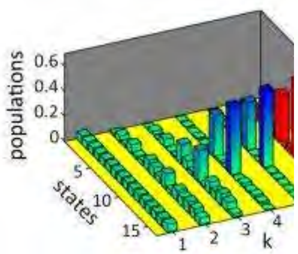
SCIENCE

QUANTUM PROCESSOR CALCULATES THAT 15 = 3X5 (WITH ALMOST 50% ACCURACY!)

By Rebecca Boyle   Posted August 20, 2012

143 is largest number yet to be factored by a quantum algorithm

April 11, 2012 by Lisa Zyga feature



Quantum factorization of 56153 with only 4 qubits

Nikesh S. Dattani,[1,2,*] *Nathaniel Bryans*[3,†]

[1] Quantum Chemistry Laboratory, Kyoto University, 606-8502, Kyoto, Japan, [2] Physical & Theoretical Chemistry Laboratory, Oxford University, OX1 3QZ, Oxford, UK, [3] University of Calgary, T2N 4N1, Calgary, Canada. [*] dattani.nike@gmail.com, [†] nbryans1@gmail.com

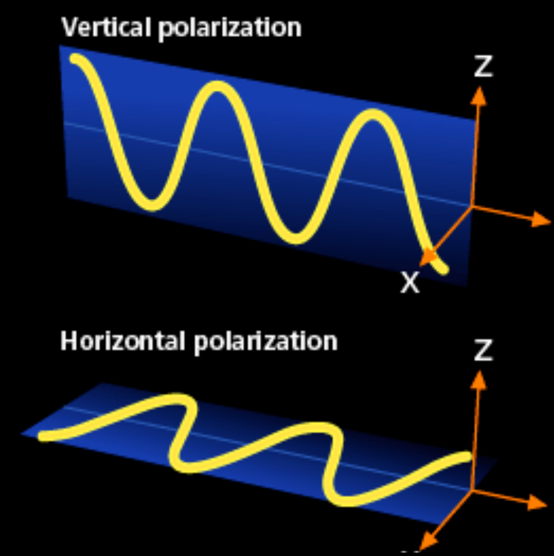
Only for numbers with special patterns

Not really the real thing (Shor)

Constructing quantum computers

Qubits obtained from **physical phenomena**

- Photons (2 polarizations)
- Molecules (2 nuclear spins)
- Superconducting (different)



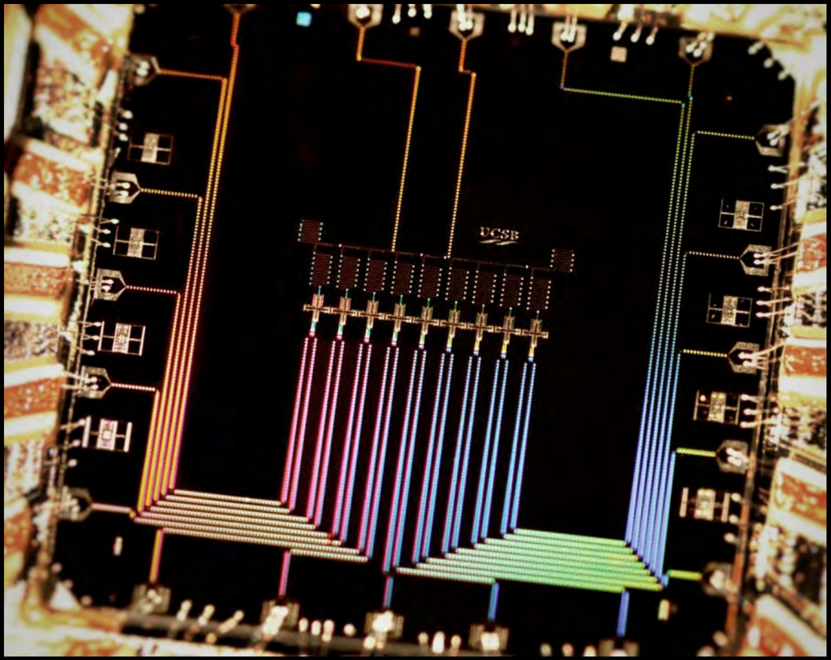
Major pain: **correction or errors**

- Qubits mixed up with the environment
- Quantum noise

Recent milestone

Partial error correction for a **9-qubit** state

Google-sponsored research group



D-Wave

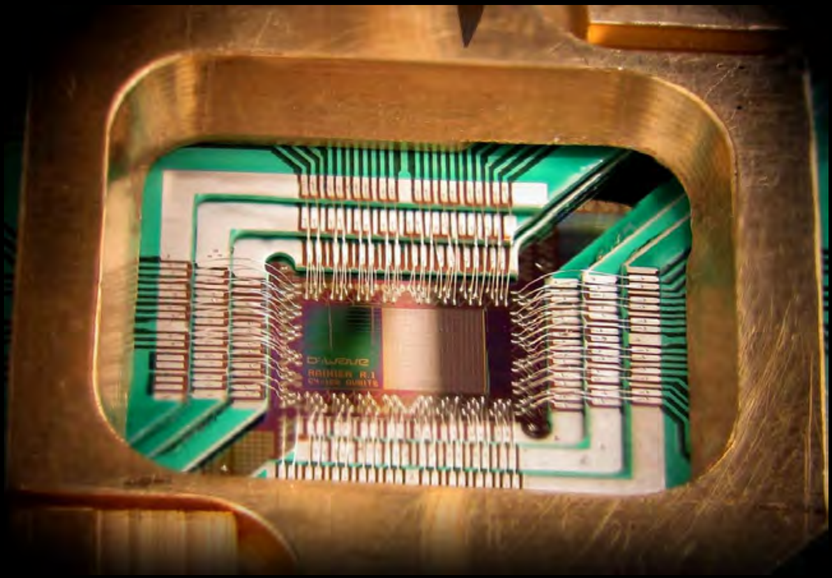
Canadian company, pioneer in QC research

Adiabatic computers, not real QC

512-qubit system

Quantum annealing

No Shor



Many challenges

Stability, error-correction

How much will cost “N quantum operations” vs “N classical operations”?

Some algorithms need **quantum RAM**, which we don’t really know how to do

Unlikely to come in the next decade, if ever

3. Breaking crypto

TL;DR: We're doomed

RSA: broken

Diffie-Hellman: broken

Elliptic curves: broken

El Gamal: broken

RSA

No more RSA encryption or signatures

Based on the hardness of **factoring**

    You know **N** = **p*q**, you search **p** and **q**

Hard on a classical computer (most probably)

Easy on a quantum computer!

Shor's idea to factor N=pq

$\mathbf{X}^{\mathbf{e}}$ mod **N** for **e** in [1, 2, 3, …] and some **X** will repeat with a period dividing (**p**-1)(**q**-1)

A period gives **information on p and q!**

Shor's algorithm:

1. Prepare qubits to encode X, X^2, X^3, X^4, … simultaneously
2. **Find the period** using the Quantum Fourier Transform
3. Exploits the period to **recover p and q**

Discrete logarithms

Problem behind **Diffie-Hellman, ECC**

You know **g** and **g**^{y}, you search **y**

Like factoring, a **Hidden Subgroup Problem**

Shor works too!

What about symmetric ciphers?

AES with a 128-bit key:

Classical: 128-bit security
Quantum: **64-bit security**

Grover's algorithm: searches in N items in $O(\sqrt{N})$ time and $O(\log N)$ memory

Solution: upgrade to 256-bit AES

4. Post-quantum crypto

Post-quantum crypto

Alternatives to RSA, Diffie-Hellman, ECC

Resistance to QC can't be totally proved

http://pqcrypto.org/

Hash-based signatures

Problem: inverting **hash functions**

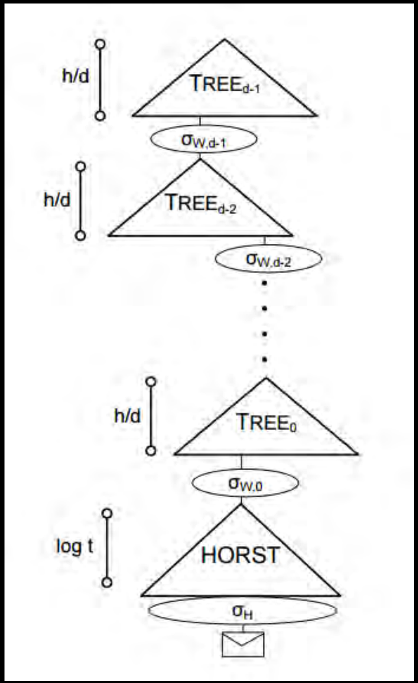
Ideas from Lamport (1979), Merkle (1989)

Example of SPHINCS:
(http://sphincs.cr.yp.to/)

41 KB signatures

1 KB public and private keys

Slow (100s signatures/sec)



Multivariate signatures

Problem: solve complex systems of equations

First ideas in the 1980s

$$0 = X_1X_2X_3 + X_1X_3 + X_2X_4$$
$$1 = X_1X_3X_4 + X_2X_3X_4$$
$$0 = X_1X_3 + X_2X_3$$

Many schemes have been broken...

Code-based crypto

Problem: decoding **error-correcting codes**

Schemes: McEliece (1979), Niederreiter (1986)

Limitations:

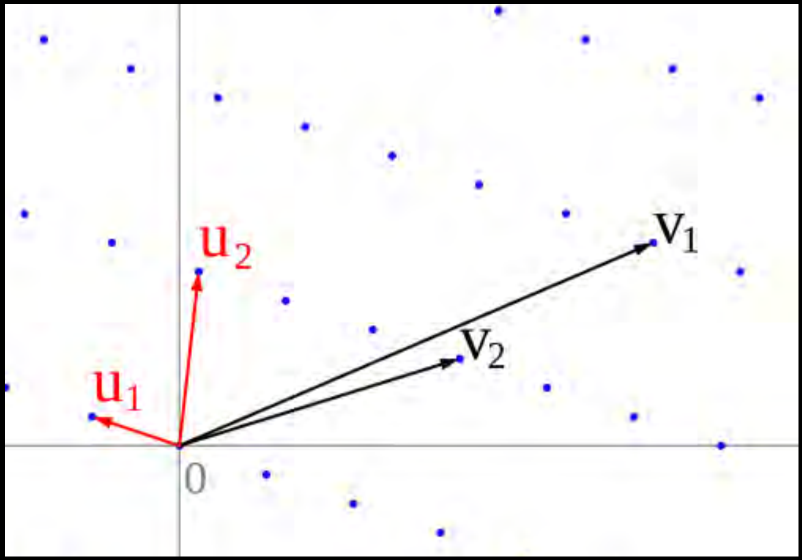
- Large keys (100 KB+)
- Fewer optimized implementations

Lattice-based crypto

Based on lattice problems (duh!)

Learning-with-errors: learn a simple function given results with random noise

Encryption, signature



5. Quantum key distribution

Quantum key distribution (QKD)

Use of quantum phenomena to **share a key**

- Kind of “quantum Diffie-Hellman”
- Not quantum computing
- Not quantum cryptography

“Security based on the laws of physics”

- Eavesdropping will cause errors
- Keys truly random

BB84

First QKD protocol, though not really quantum

Idea:

- Send bits in the form of polarized photons
- Can be observed in 2 ways, only one is right

Alice's random bit	0	1	1	0	1	0	0	1
Alice's random sending basis	+	+	×	+	×	×	×	+
Photon polarization Alice sends	↑	→	↘	↑	↘	↗	↗	→
Bob's random measuring basis	+	×	×	×	+	×	+	+
Photon polarization Bob measures	↑	↗	↘	↗	→	↗	→	→
PUBLIC DISCUSSION OF BASIS								
Shared secret key	0		1			0		1

Caveats

Like any security system, it's complicated

Security

Quantum cryptography is secure… except when it's not

Researchers close one security hole in quantum key distribution, but seem to …

Eventually relies on **classical crypto**

Typically with frequent rekeying

QKD **implementations** have been attacked

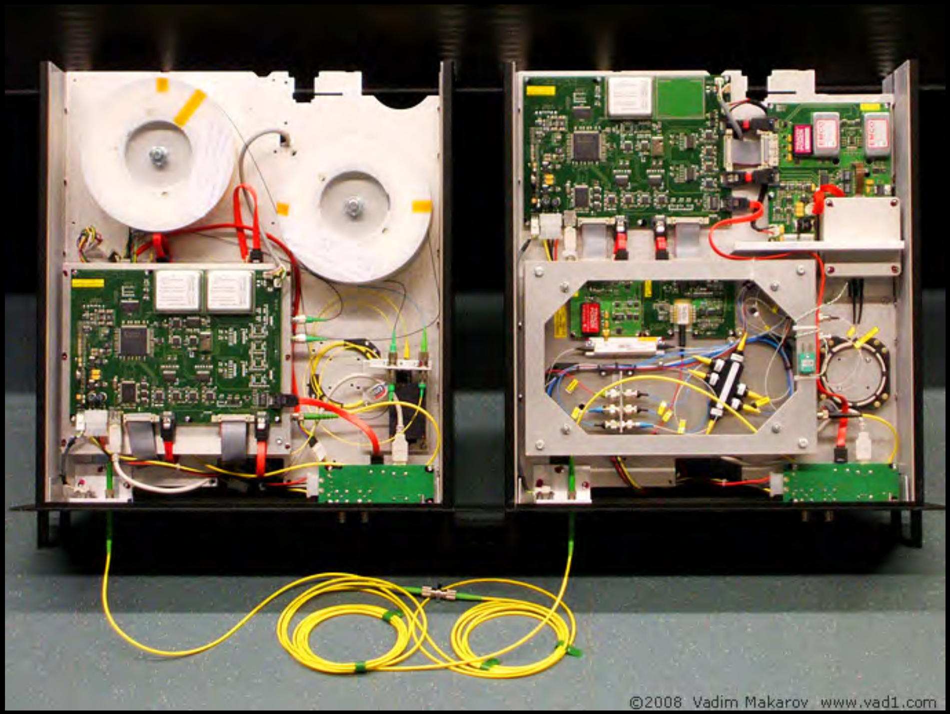
"Quantum hacking"

(formerly NTNU, Norway)

Deployment

Dedicated optical fiber links

Point-to-point, limited distance (< 100 km)



6. Quantum copy protection

Quantum copy protection

Idea: leverage the **no-cloning principle**
(cos you can't know everything about something)

Quantum cash

Impossible to counterfeit**, cos' physics** (1969)

Bills include qubits with some secret encoding

Only the bank can authenticate bills...

Publicly verifiable quantum cash

Anyone can verify that a bill isn't counterfeit

Uses public-key crypto, non-quantum

Can be secure even with black-box verification

Quantum software protection

Using quantum techniques:

- "Obfuscate" the functionality
- Make copies impossible

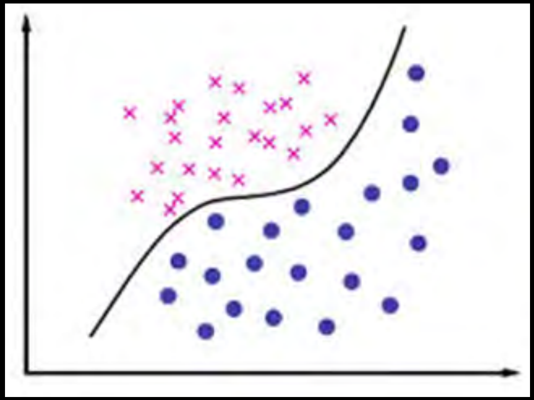
```
verify(pwd) {
   return pwd == "p4s5w0rD"
}
```

1. Turn `verify()` into a list of qubits
2. Verification: apply a transform that depends on `pwd`, then measure the qubits

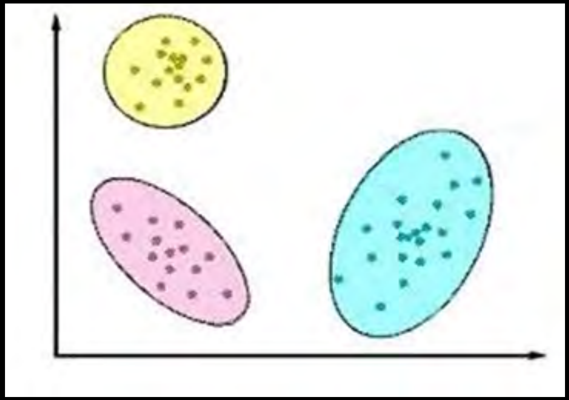
7. Quantum machine learning

Machine learning

“Science of getting computers to act without being explicitly programmed” —Andrew Ng



Supervised



Non-supervised

Successful for spam filtering, fraud detection, OCR, recommendation systems

Machine learning and security

No silver bullet, but may help

ML being used for

- **Intrusion detection** (network, endpoint)
- Binary vulnerability discovery

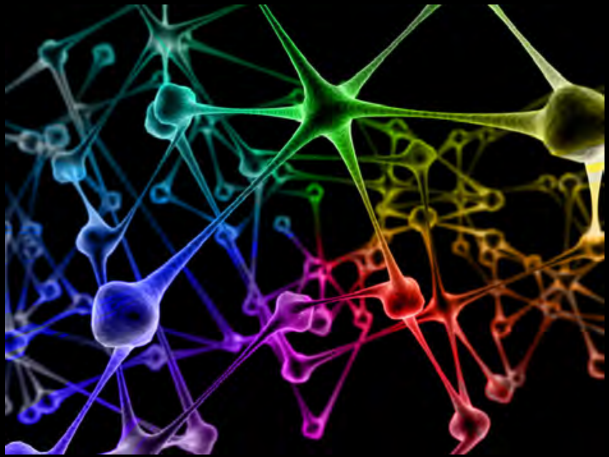
Nevertheless, vendors give neither

- Details on the techniques used, nor
- Effectiveness figures or measurements

Quantum machine learning

"Port" of basic ML techniques to QC, like

- k-mean clustering
- Neural networks
- Support vector machines



Many use **Grover** for a **square-root speedup**

Potential exponential speedup, but...

Quantum RAM (QRAM)

Awesome concept

- Addresses are given in superposition
- Read values are retrieved in superposition

Many QML algorithms need QRAM

But it'd be extremely **complicated to build**

8. Conclusions

Quantum computers s***

Because they…

- ARE NOT superfaster computers
- WOULD NOT solve NP-hard problems
- MAY NEVER BE BUILT anyway

Quantum computers are awesome

Because they...

- Would DESTROY all pubkey crypto deployed
- Give a new meaning to "COMPUTING"
- May teach us a lot about physics and Nature

Thank you!