# The Potential Impact of Quantum Computers on Society

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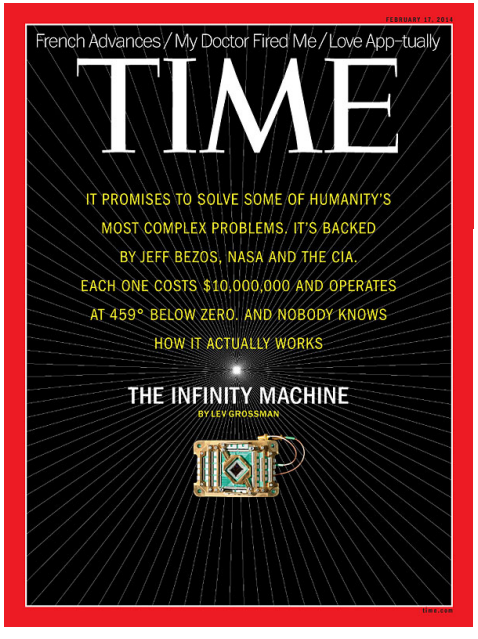
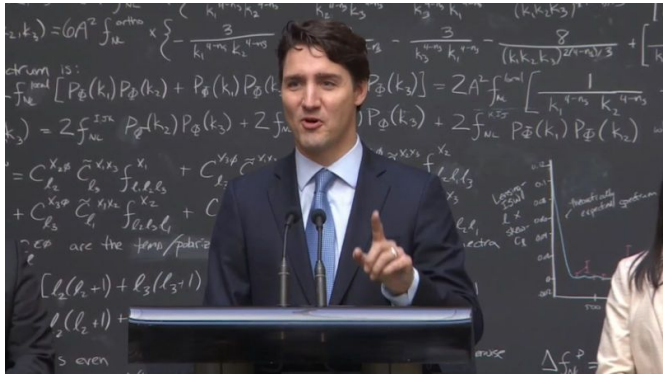
# Lots of money! Massive impact?

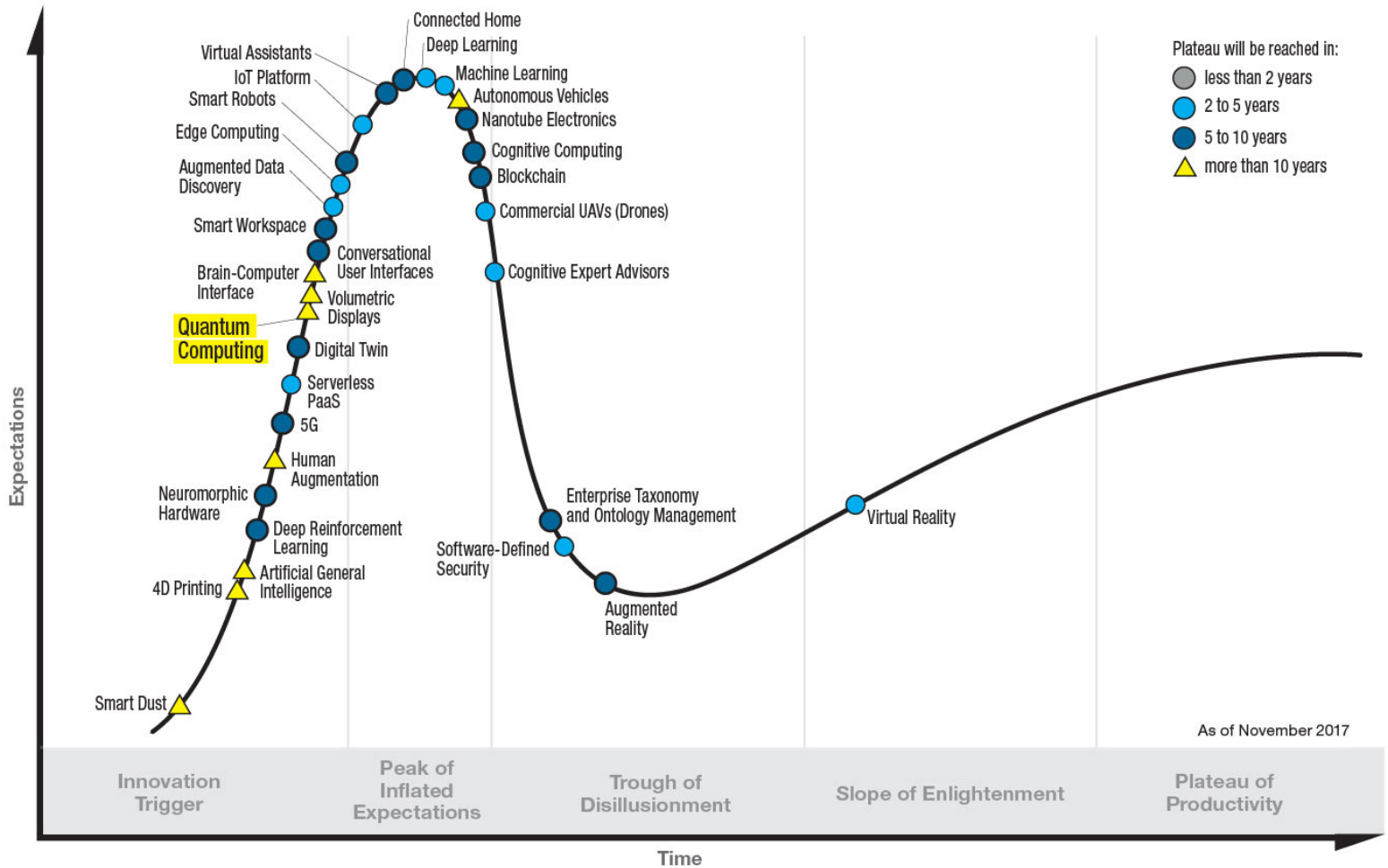






# Gartner Hype Cycle for Emerging Technologies




**gartner.com/SmarterWithGartner**

Source: Gartner (November 2017)



Gartner

# Quantum computers: hype vs substance

Goal of this talk:

*Assume large quantum computers will be built in the next decades.*

**Where will they have a real impact?**

# Quantum bits

- A classical bit is 0 or 1
- Quantum mechanics allows superposition of $|0\rangle$ and $|1\rangle$, each with its own "amplitude". This is a qubit
- We can use any physical system with two distinguishable basis states to build a qubit:

  electron spin, photon polarization, $|$  $\rangle + |$  $\rangle$

- 2 qubits: superposition of 4 possible basis states

  3 qubits: superposition of 8 possible basis states

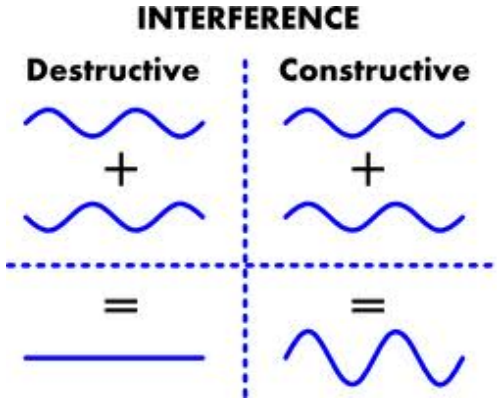
  $\vdots$

  $n$ qubits: superposition of $2^n$ possible basis states

  Described by a "wavefunction": vector of all $2^n$ amplitudes

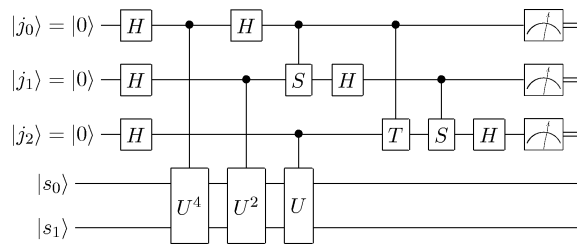
# Quantum computers in a nutshell

- Waves can strengthen or weaken each other:




- Quantum computation = superposition + interference

1. Start with qubits in some simple state (e.g. all $|0\rangle$)
2. Run circuit of "elementary gates" creating the right interference, so the final state has most of its weight on solutions to your problem




3. Measuring the final state then gives solution

# Where do we stand today?

- We are entering the NISQ era (Preskill'18):
  Noisy Intermediate-Scale Quantum technology
- IBM, Google, Intel are close to 50-70 reasonably good qubits.

  But 50-70 qubits is not a lot: classical computers have billions of bits. And "reasonably good" is also not great
- We'll need error-correction to deal with errors,
  and that will require many more physical qubits
- "Quantum supremacy" may be reached soon:
  some quantum computation that cannot be simulated on today's best supercomputers in a reasonable amount of time
- But useful quantum supremacy is still years away

# Quantum computers: hype vs substance

Goal of this talk:

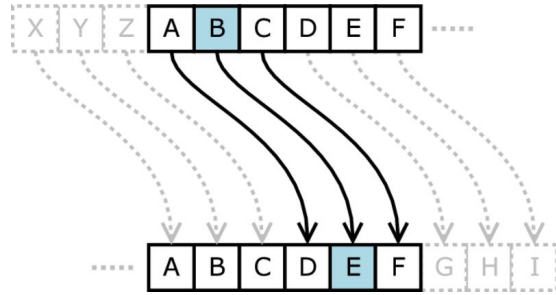
*Assume large quantum computers will be built in the next decades.*

**Where will they have a real impact?**

- Probably: Cryptography, optimization, simulation
- Maybe: Machine learning
- Forget about it: NP-hard problems (TSP, protein folding,...), ending climate change, finding ET, ...

# Potential impact area 1: cryptography

- The ancient art of secret communication

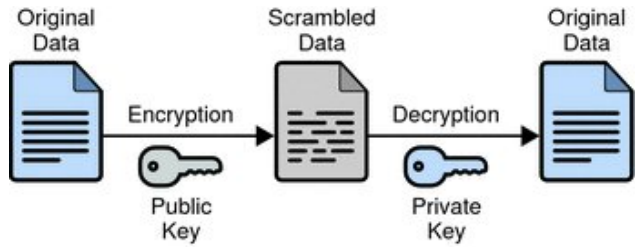



- Julius Caesar encrypted his letters by shifting the alphabet (easy to break)
- The nazis encrypted their messages using fancy "Enigma" machines with secret settings that changed every day (broken by Turing and others using the first computers)

- Since the 1970s: more systematic, mathematical study
- Two branches: codemakers and codebreakers

# Codebreaking

- Public-key cryptosystems are great:
  - you choose private key and public key
  - everybody with the public key can send you encrypted messages
  - messages can only be decrypted by someone with the private key (=only you)




*. . . unless they can solve some hard math problem*

- Most public-key crypto is based on the assumed hardness of
  - factoring large integers (RSA), or
  - finding discrete logarithms (Diffie-Hellman, Elliptic curve)
- Shor's algorithm breaks this using a few thousand good qubits
- Symmetric crypto systems like AES are more secure, but require shared secret key

# Is this an imminent threat?


- Relax, quantum computers ain't gonna happen anytime soon...

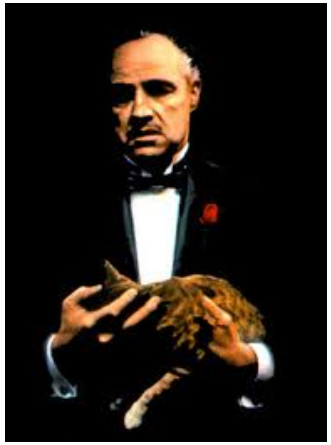
- Maybe, maybe not.

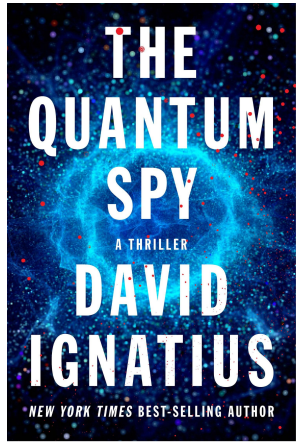
  But many countries have laws requiring top-secret documents to be protected for the next 20-30 years.

  If somebody steals your encrypted records now and decrypts it 10 years later using a quantum computer, that's still bad.

- Also, changing our crypto infrastructure will take a long time

- So, how to fix cryptography against quantum adversaries?

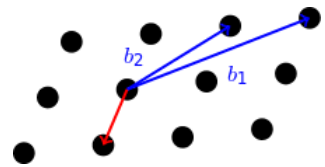


# Classical codemaking: post-quantum cryptography

- Minimal adaptation: keep the idea of public-key crypto, but base it on other math problems than factoring or discrete log.

  Prominent examples: lattice problems, error-correcting code problems, ...



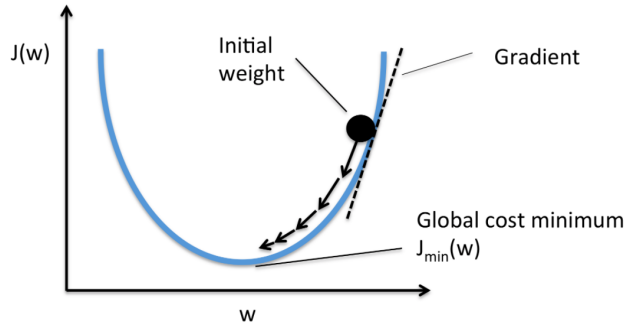

- Advantages: Users only need classical computers, we can keep our efficient public-key infrastructure
- Disadvantages: Are these systems secure against quantum computers? Who knows; not enough research yet
- NIST is running a competition for the best candidate scheme

# Quantum codemaking: quantum cryptography

- Use quantum to induce an information-gain-vs-disturbance tradeoff: if adversary learns a lot about state of quantum channel, then they necessarily disturb it, and will be detected
- BB'84 key distribution: Alice and Bob can obtain a shared secret key by communicating over a *public* quantum channel and a *public authenticated* classical channel
- Advantages: Information-theoretic security, even against quantum adversary. Doable with current technology
- Disadvantages: Inefficient point-to-point communication. Limited distance. Current implementations have been hacked.

# Potential impact area 2: optimization

- Optimization is one of the main applications of computers in the real world: allocating resources to jobs, scheduling lectures, optimizing designs, minimizing energy use, etc.
- Quantum computers can help:
  - Grover's search algorithm
  - Finding the shortest path on a map
  - Speed-ups for convex optimization
  - Gradient descent towards minimum




- Typically these only give limited ("polynomial") speed-up; whether that's worthwhile depends on the cost of a QC
- Classical input needs to be accessible in superposition, so needs to be stored in Quantum Random Access Memory

# Quantum machine learning

- Machine learning has gotten hugely successful in the last 5 years


- After choosing set $\mathcal{M}$ of possible models & cleaning up data, machine learning boils down to an optimization problem:

  $$\max_{m \in \mathcal{M}} \text{ fit of } m \text{ with the data}$$

  Quantum computers can speed this up (in some cases)

- Often the data consists of vectors in some large dimension $d$. Can try to prepare those as $\log_2(d)$-qubit states, manipulate those with quantum algorithms. Easier said than done...

# Potential impact area 3: simulation

- Much effort on understanding quantum systems for materials, batteries, drugs, high-temperature superconductivity etc.
- Sophisticated classical methods hit a wall for larger systems.

  That's why Feynman'82 wanted a *quantum* computer:

  "the full description of quantum mechanics for a large system with R particles [...] because it has too many variables, it cannot be simulated with a normal computer with a number of elements proportional to R."
  [...]
  "Can a quantum system be probabilistically simulated by a classical (probabilistic, I'd assume) universal computer? In other words, a computer which will give the same probabilities as the quantum system does. If you take the computer to be the classical kind I've described so far, (not the quantum kind described in the last section) and there are no changes in any laws, and there's no hocus-pocus, the answer is certainly, No!"

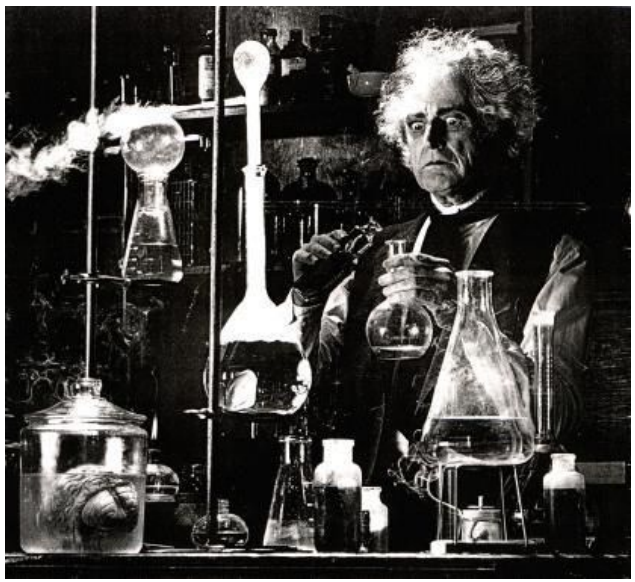
# Fighting quantum with quantum

- Think of quantum computer as universal quantum simulator: given a sufficiently simple description of a physical system ("local Hamiltonian"), a quantum computer can simulate the evolution of a given initial state for some time $t$
- Initially, in the 1980s and 1990s:
  complexity of the quantum simulator was "polynomial"
- In the last 5 years, such "Hamiltonian simulation" has been optimized, and people are starting to apply this to real physical systems of interest,
  like nitrogen-fixation for more efficient production of fertilizer

# Quantum simulation could have huge impact

- A few hundred good qubits (and lots of gates. . . ) suffice to do interesting things in quantum chemistry, so this is likely to be among the first real applications of quantum computers

- There could be quantum version of the "maker movement" or SETI: lots of amateurs start to explore and toy around with simulations of large molecules. Who knows what will be discovered!



# Summary so far

- Quantum computers are great

  not as great as some journalists make you think

  but much stronger than our current computers in some areas

- Should society be happy?

- Or afraid?

# Risks to society: breakdown of crypto

- Large quantum computers can break all crypto that's based on factoring and discrete log

- Scenario 1: someone builds a QC, doesn't tell anyone, but uses it to read your email & steal your money
- Scenario 2: someone builds a QC, proudly announces this, and uses it to read your email & steal your money
- Either way, after a while this hacking is detected, and then all confidence in our current crypto schemes will disappear
- Fortunately, by then we should have tools to fix this: post-quantum crypto and quantum crypto

# Risks to society: inequality

- Quantum computers are extremely expensive to build, and will probably remain so for a long time
- What if only one or a few parties can afford to build one?
- Inequality between countries: it's possible that only the US government will have a QC (at least for a while), like with the atomic bomb

- Inequality between companies: suppose QC is great for designing new medicines, and only company X has one. All other companies go out of business $\Rightarrow$ monopoly, so medicine prices will go through the roof

# Mitigating inequality

- Hopefully quantum computing power becomes available widely through the cloud, like IBM Q Experience
- What if the market doesn't provide this,

  or governments try to prevent it?

  Possible solution:
  Santa Claus gives
  the world a quantum computer

Santa's little helpers: Norway, Gates Foundation, ...

# Summary

- Quantum computation & information is wonderful science
- Quantum computers may become powerful practical machines, but that is still some years (decades?) away.

  But in the NISQ era we can at least start to experiment
- Main areas where quantum computers may impact society:
  1. Cryptography
  2. Optimization
  3. Simulation of quantum systems
- Main risks to society:
  1. Breakdown of current cryptography
     *post-quantum or quantum crypto will save us*
  2. Increased inequality between countries, companies
     *the cloud will save us (or Santa Claus)*