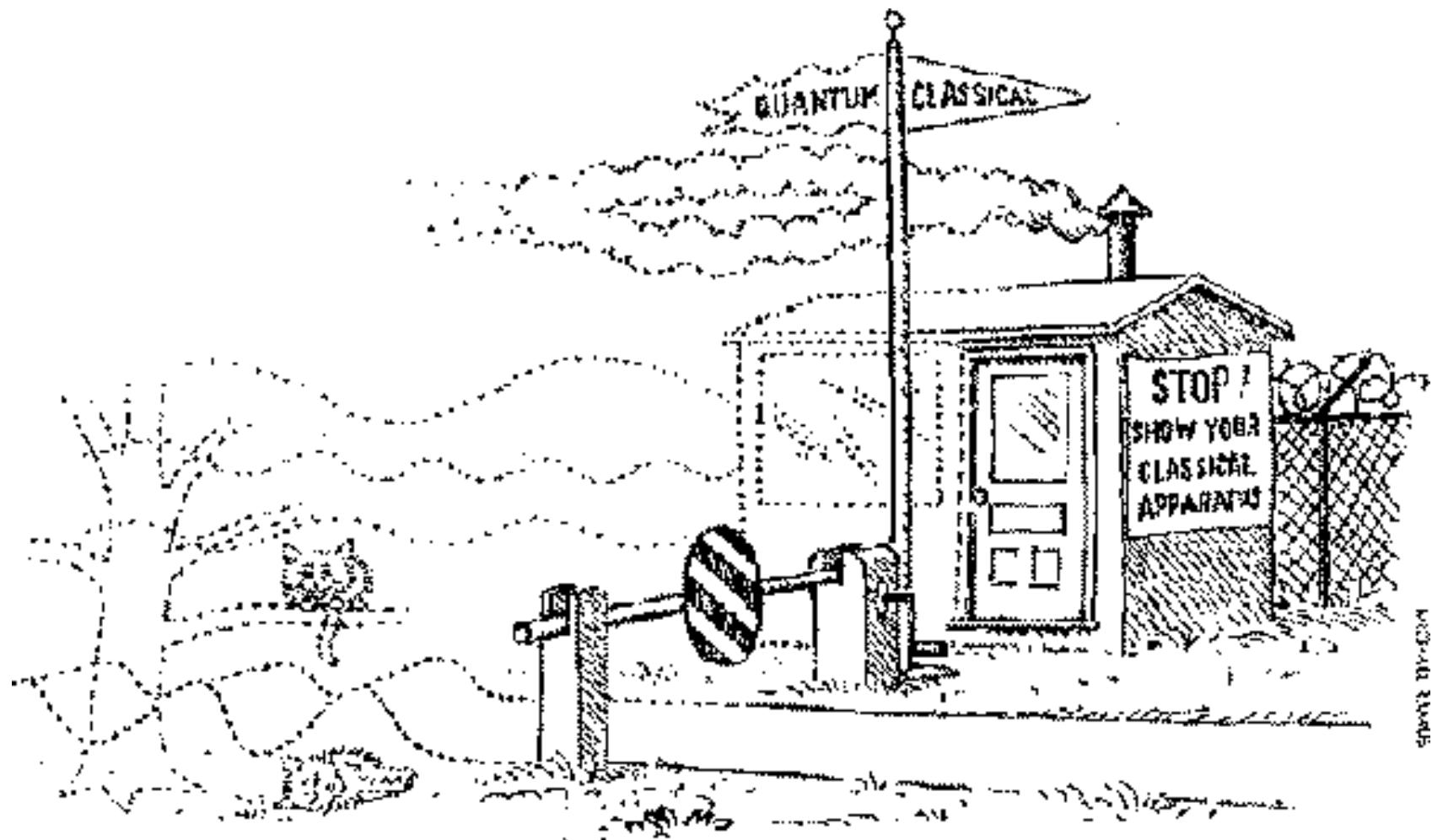


Quantum Computing



KODAK SAFETY FILM

Information is Physical

information is always tied to a physical realization

fundamental limits:

speed-limit: c (relativity)

resetting a bit costs $> kT \ln 2$ (statistical mechanics)

dynamical RAM represents bit by charge on capacitor:

Cbit

$b=1$ – capacitor charged

$b=0$ – capacitor uncharged

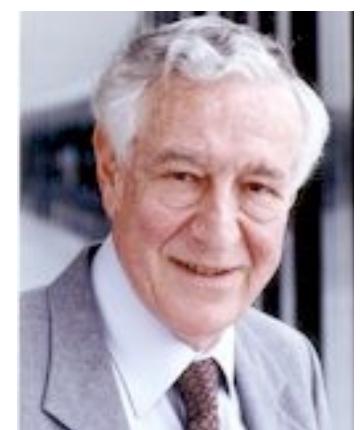
Qbit

alternative: **represent bit by spin- $\frac{1}{2}$**

$$| b \rangle = \alpha | 0 \rangle + \beta | 1 \rangle$$

superposition of (classical) bits

Rolf Landauer



Quantum Information

Qbits cannot be copied
(no-cloning theorem)

disadvantage:
information in Qbit not fully accessible
(uncertainty!)

advantage:
eavesdropping on a quantum channel detectable
⇒ quantum cryptography

No-Cloning Theorem

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LETTERS TO NATURE

A single quantum cannot be cloned

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If a photon of definite polarization encounters an excited atom, there is typically some nonvanishing probability that the atom will emit a second photon by stimulated emission. Such a photon is guaranteed to have the same polarization as the original photon. But is it possible by this or any other process to amplify a quantum state, that is, to produce several copies of a quantum system (the polarized photon in the present case) each having the same state as the original? If it were, the amplifying process could be used to ascertain the exact state of a quantum system: in the case of a photon, one could determine its polarization by first producing a beam of identically polarized copies and then measuring the Stokes parameters¹. We show here that the linearity of quantum mechanics forbids such replication, and that this conclusion holds for all quantum systems.

Note that if photons could be cloned, a plausible argument could be made for the possibility of faster-than-light communication². It is well known that for certain non-separably correlated Einstein-Podolsky-Rosen pairs of photons, once an observer has made a polarization measurement (say, vertical versus horizontal) on one member of the pair, the other one, which may be far away, can be for all purposes of prediction regarded as having the same polarization³. If this second photon could be replicated and its precise polarization measured as above, it would be possible to ascertain whether, for example, the first photon had been subjected to a measurement of linear or circular polarization. In this way the first observer would be able to transmit information faster than light by encoding his message into his choice of measurement. The actual impossibility of cloning photons, shown below, thus prohibits superluminal communication by this scheme. That such a scheme must fail for some reason despite the well-established existence of long-range quantum correlations^{4–8}, is a general consequence of quantum mechanics⁹.

A perfect amplifying device would have the following effect

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it is impossible to copy an unknown quantum state
proof by *reductio ad absurdum*

on an incoming photon with polarization state $|s\rangle$:let U be unitary cloning operator: $U|\Psi\rangle|s\rangle = |\Psi\rangle|\Psi\rangle$ for any $|\Psi\rangle$
then $\langle s|\langle\Psi|U^\dagger \cdot U|\Phi\rangle|s\rangle$

$$|A_0\rangle(\downarrow) \rightarrow |A_{\text{vert}}\rangle(\ddagger) \quad (2)$$

and

$$|A_0\rangle(\leftrightarrow) \rightarrow |A_{\text{hor}}\rangle(\ddagger) \quad (3)$$

According to quantum mechanics this transformation should be representable by a linear unitary cloning operator. It therefore follows that if the final state is total, the polarization given by the linear combination $|\alpha\rangle\downarrow + |\beta\rangle\leftrightarrow$ — for example, it could be linearly polarized in a direction 45° from the vertical, so that $\alpha = \beta = 2^{-1/2}$ — the result of its interaction with the apparatus will be the superposition of equations (2) and (3):

$$|A_0\rangle(\alpha\downarrow + \beta\leftrightarrow) \rightarrow |A_{\text{vert}}\rangle(\ddagger) + \beta|A_{\text{hor}}\rangle(\ddagger) \quad (4)$$

If $|\alpha\rangle\downarrow + |\beta\rangle\leftrightarrow$ is the final state of the apparatus, then the two photons emerging from the apparatus are in the fixed state of polarization. If these apparatus states are identical, then the two photons are in the pure state

$$\alpha|\ddagger\rangle + \beta|\ddagger\rangle \quad (5)$$

In neither of these cases is the final state the same as the state with two photons both having the polarization $|\alpha\rangle\downarrow + |\beta\rangle\leftrightarrow$. That state, the one which would be required if the apparatus were to be a perfect amplifier, can be written as

$$2^{-1/2}(\alpha|A_{\text{vert}}\rangle + \beta|A_{\text{hor}}\rangle)^2|0\rangle = \alpha^2|\ddagger\rangle + 2^{1/2}\alpha\beta|\downarrow\leftrightarrow\rangle + \beta^2|\ddagger\rangle$$

which is not equal to equation (5). Thus no apparatus exists which will amplify an arbitrary polarization. The above argument does not rule out the possibility of a device which can amplify two special polarizations, such as vertical and horizontal. Indeed, any measure which distinguishes between vertical and horizontal polarization, for example, could be used to clone a photon.

The same argument can be applied to any other kind of quantum system. As in the case of photons, linearity does not forbid the amplification of any given state by a device designed especially for that state, but it does rule out the existence of a device capable of amplifying an arbitrary state.

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Milonni (unpublished work) has shown that the process of stimulated emission does not lead to quantum amplification, because if there is stimulated emission there must also be — with equal probability in the limit — stimulated absorption. A stimulated photon is entirely independent of the polarization of the original.

It is conceivable that a more sophisticated amplifying apparatus could get around Milonni's argument. We have therefore devised a more sophisticated cloning machine which, while it is more complicated, can amplify an arbitrary polarization.

We stress that the question of replicating individual photons is of practical interest. It is obviously closely related to the

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quantum limits on the noise in amplifiers^{10,11}. Moreover, an experiment devised to establish the extent to which polarization of single photons can be replicated through the process of stimulated emission is under way (A. Gozzini, personal communication; and see ref. 12). The quantum mechanical prediction is quite definite; for each perfect clone there is also one randomly polarized, spontaneously emitted, photon.

We thank Alain Aspect, Carl Caves, Ron Dickman, Ted Jacob, Peter Milonni, Marlan Scully, Pierre Meystre, Don Jacobs, and John Archibald Wheeler for enjoyable and stimulating discussions.

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lower than the solar oxygen-to-hydrogen ratio means that at least 90% of the ejected material must have come from the helium layer.

Arnett (ref. 7 and refs therein) systematically evolved helium cores of various masses (M_\odot) into late stages of evolution. He compared Davidson's⁸ derived abundances of the Crab nebula with calculated abundances from the $M_\odot = 4.0 M_\odot$ model, which was his lowest-mass, highly evolved helium core (corresponding to approximately a $15 M_\odot$ star). Combining all the material above the helium-burning shell (his case B) with enough interstellar material to obtain $X_{\text{He}}/X_H = 8$, he found good agreement with $X_{\text{He}}/X_{\text{He}}$ and $X_{\text{O}}/X_{\text{He}}$ of Davidson's⁸ 'model 1'. However, the calculated value of $X_{\text{C}}/X_{\text{He}}$ was too large by a factor of 30. At that time, the Crab's carbon abundance had not been directly measured and Arnett suggested several possibilities: the inferred carbon abundance was too low, the carbon was hidden in the filaments, or a lower-mass helium core, $\sim 3 M_\odot$, was more appropriate.

Using recent UV observations with the International Ultraviolet Explorer, Davidson *et al.*⁷ have established that the carbon abundance is nearly solar. They also showed that the hydrogen and helium seemed to be fairly well mixed and, as carbon is convectively mixed in the helium layer, this would indicate against carbon being hidden in the filaments. However, the observations of Dennefeld and Andrillat⁹ showed that the strength of [C i] $\lambda 9,850$ relative to [S iii] $\lambda 9,069$ varied with position in the Crab. The strongest [C i] line would indicate a rather large carbon abundance if the ionizing flux is constant. Whether the IR observations indicate variation in the carbon abundance, variation in the ionizing flux, or high densities in neutral cores is not known. For the remainder of this report we will assume the carbon abundance as determined by Davidson *et al.*⁷.

The existence of a pulsar in the Crab indicates that the progenitor's mass was larger than the upper mass limit ($8 \pm 1 M_\odot$)¹⁰ for degenerate carbon ignition. Degenerate carbon ignition results in carbon deflagration¹¹ which completely disrupts the star, leaving no compact remnant. Lower-mass stars that lose enough mass to avoid degenerate carbon burning eventually become white dwarfs. Stars massive enough ($\geq 8 M_\odot$) to burn carbon non-degenerately will eventually undergo a core collapse initiated either by electron capture¹² onto Mg, Ne and O or by burn-out of all the available fuel^{13,14}. When the collapsing core reaches neutron-star densities, stability is regained. Although detailed calculations of the collapse remain inconclusive, it is generally felt that the core will overshoot its equilibrium position and then rebound, initiating a shock wave⁴. This shock wave ejects the outer material but not the core, resulting in both a supernova nebula and a pulsar¹⁵. In more massive stars

\Rightarrow only orthogonal basis states can be cloned
(reversible copying of Cbits)

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classical logics

Boolean operations

NOT gate

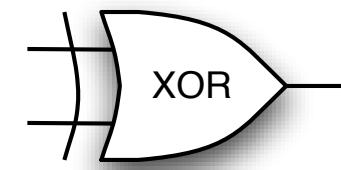
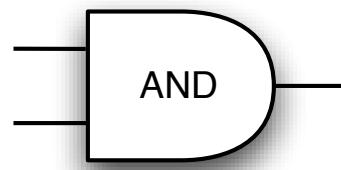
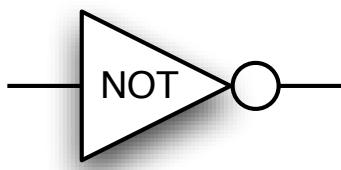
a	$\neg a$
0	1
1	0

AND gate

a	b	$a \cdot b$
0	0	0
0	1	0
1	0	0
1	1	1

XOR gate

a	b	$a \oplus b$	a
0	0	0	0
0	1	1	0
1	0	1	1
1	1	0	1



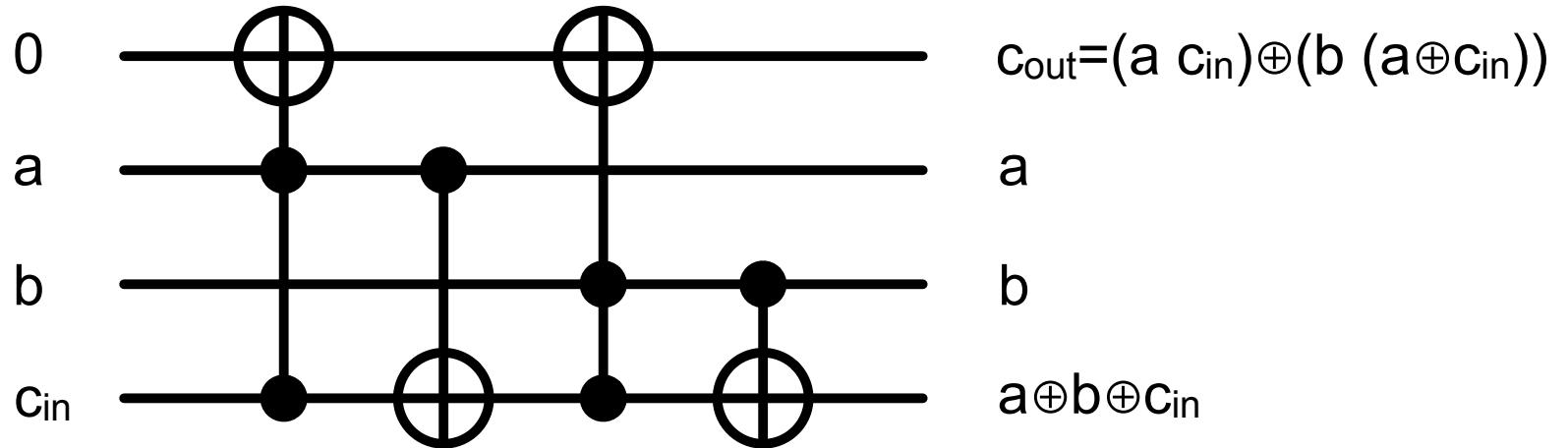
not reversible!

reversible: cNOT

reversible logics

e.g. controled NOT and Toffoli gates

example:
full adder



reversible gate defines operation on basis states
naturally extends to unitary operators

quantum gates without classical analogon:
e.g. Hadamard gate (creates superpositions)

$$U_H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$U_H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

quantum parallelism

$$U_H|0\rangle U_H|0\rangle \dots U_H|0\rangle = U_H^{\otimes n}|00\dots 0\rangle = \sum_x |\mathbf{x}\rangle$$

superposition of all 2^n basis states

implement classical function $f(x)$ as unitary operator:

$$U_f|\mathbf{x}\rangle|\mathbf{y}\rangle := |\mathbf{x}\rangle|\mathbf{y} \oplus f(\mathbf{x})\rangle$$

then $U_f U_H^{\otimes n}|\mathbf{0}\rangle|\mathbf{0}\rangle = U_f \sum_x |\mathbf{x}\rangle|\mathbf{0}\rangle = \sum_x \underbrace{|\mathbf{x}\rangle|f(\mathbf{x})\rangle}_{x \text{ and } f(x) \text{ entangled!}}$

simultaneous evaluation of 2^n function values!

problem: only one (random!) $f(x)$ can be measured

**The Art of Quantum Computing:
use interference to extract relevant information**

dimension of Hilbert space

n-Qbit Hilbert space dimension

n	2^n		
10	1,024	kb	kilo
20	1,048,576	Mb	Mega
30	1,073,741,824	Gb	Giga
40	1,099,511,627,776	Tb	Tera
50	1,125,899,906,842,620	Pb	Peta
60	1,152,921,504,606,850,000	Eb	Exa
70	1,180,591,620,717,410,000,000	Zb	Zetta
80	1,208,925,819,614,630,000,000,000	Yb	Yotta

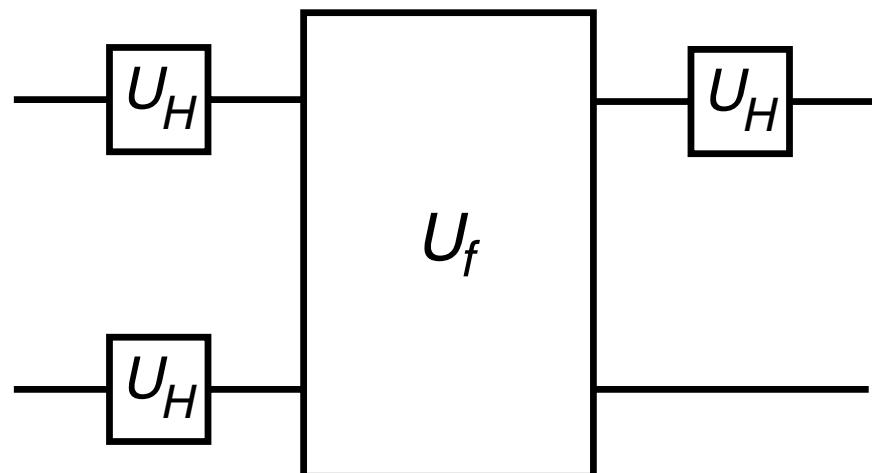
Deutsch algorithm

Proc. Roy. Soc. London, Ser. A **400**, 97 (1985)

given $f: \{0,1\} \rightarrow \{0,1\}$ is $f(0)=f(1)$ or not?

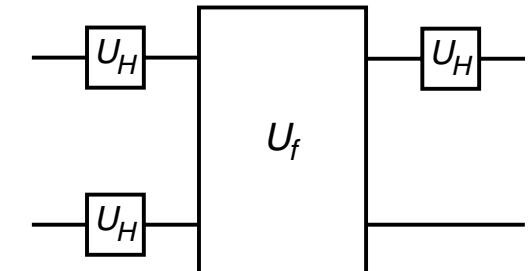
classical computing: need two calls to f

quantum computing: single call to f sufficient



Deutsch algorithm

Proc. Roy. Soc. London, Ser. A **400**, 97 (1985)



prepare superposition

$$\begin{aligned} U_H|0\rangle U_H|1\rangle &= \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \\ &= \frac{1}{2} \begin{pmatrix} |0\rangle|0\rangle & -|0\rangle|1\rangle & +|1\rangle|0\rangle & -|1\rangle|1\rangle \end{pmatrix} \end{aligned}$$

evaluate f (using $0 \oplus a = a$ and $1 \oplus a = \bar{a}$)

$$\begin{aligned} &\xrightarrow{U_f} \frac{1}{2} \left(|0\rangle|0\oplus f(0)\rangle - |0\rangle|1\oplus f(0)\rangle + |1\rangle|0\oplus f(1)\rangle - |1\rangle|1\oplus f(1)\rangle \right) \\ &= \frac{1}{2} \left(|0\rangle|f(0)\rangle - |0\rangle|\overline{f(0)}\rangle + |1\rangle|f(1)\rangle - |1\rangle|\overline{f(1)}\rangle \right) \\ &= \frac{1}{2} \left(|0\rangle [|f(0)\rangle - |\overline{f(0)}\rangle] + |1\rangle [|f(1)\rangle - |\overline{f(1)}\rangle] \right) \end{aligned}$$

interference step

$$= \begin{cases} \frac{1}{2}(|0\rangle + |1\rangle) [|f(0)\rangle - |\overline{f(0)}\rangle] \xrightarrow{U_H} \frac{1}{\sqrt{2}}|0\rangle [|f(0)\rangle - |\overline{f(0)}\rangle] & \text{if } = \\ \frac{1}{2}(|0\rangle - |1\rangle) [|f(0)\rangle - |\overline{f(0)}\rangle] \xrightarrow{U_H} \frac{1}{\sqrt{2}}|1\rangle [|f(0)\rangle - |\overline{f(0)}\rangle] & \text{if } \neq \end{cases}$$

Quantum Computing

notion of computability unchanged
quantum systems can be simulated on a classical computer

computational complexity reduced:
quantum computers can be much faster than classical ones

problem	classical algorithm	quantum algorithm
factoring N	number field sieve $O(e^{(\log N)^{1/3} (\log \log N)^{2/3}})$	Shor algorithm: $O(\log^3 N)$
unstructured search in N items	brute force: $O(N)$	Grover algorithm: $O(\sqrt{N})$

Shor algorithm

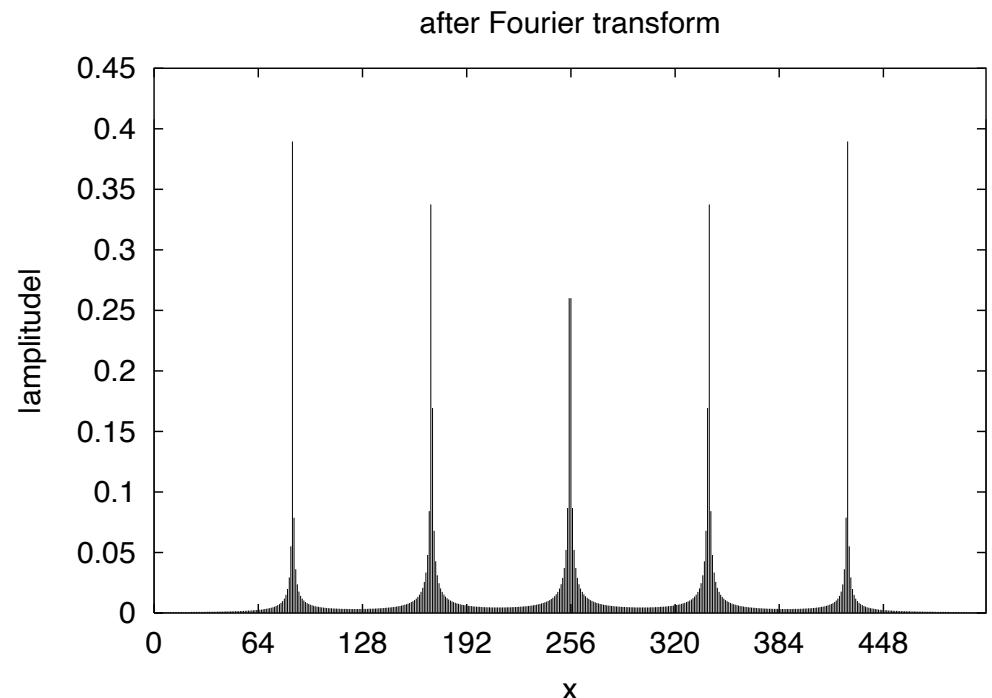
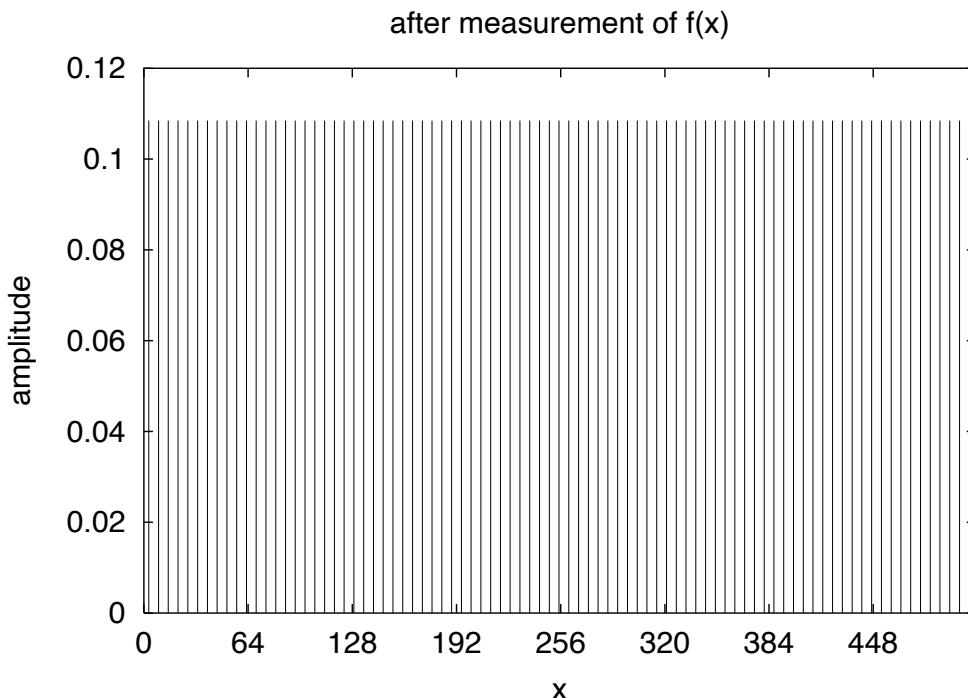
factorize M

pick $a > 1$ with $\text{gcd}(M, a)=1$ (otherwise factor found already)

calculate $f(x)=a^x \bmod M$

find period $f(x+r) = f(x)$ (quantum Fourier transform)

then $\text{gcd}(a^{r/2} \pm 1, M)$ gives factor of M



probabilistic result for r , but easy to check if correct!

factoring with bc

```
#!/usr/bin/env bc -q
define gcd(a,b) {
    auto r;
    while(a%b > 0) { r=a%b; a=b; b=r; }
    return(b);
}
define fact(m,a) { /* find factor of m with aux a>1 */
    auto e,x,r,p;
    if (a<=1) a=2; /* otherwise error */
    e=gcd(m,a); if (e>1) return(e);
    /* find period of f(x)=a^x mod m; note that f(0)=1 */
    for (x=1; a^x % m != 1; x++) r=x
    p=a^(r/2)
    e=gcd(m,p+1); if (e>1) return(e);
    e=gcd(m,p-1); if (e>1) return(e);
}

fact(21,5)
3
fact(21,250)
3
```

Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

$$U_p \frac{1}{\sqrt{2^n}} \sum_{x=0}^{2^n-1} |x, 0\rangle = \frac{1}{\sqrt{2^n}} \sum |0, p(x)\rangle = \frac{1}{\sqrt{2^n}} \left(\sum_{x \neq x_p} |x, 0\rangle + |x_p, 1\rangle \right)$$

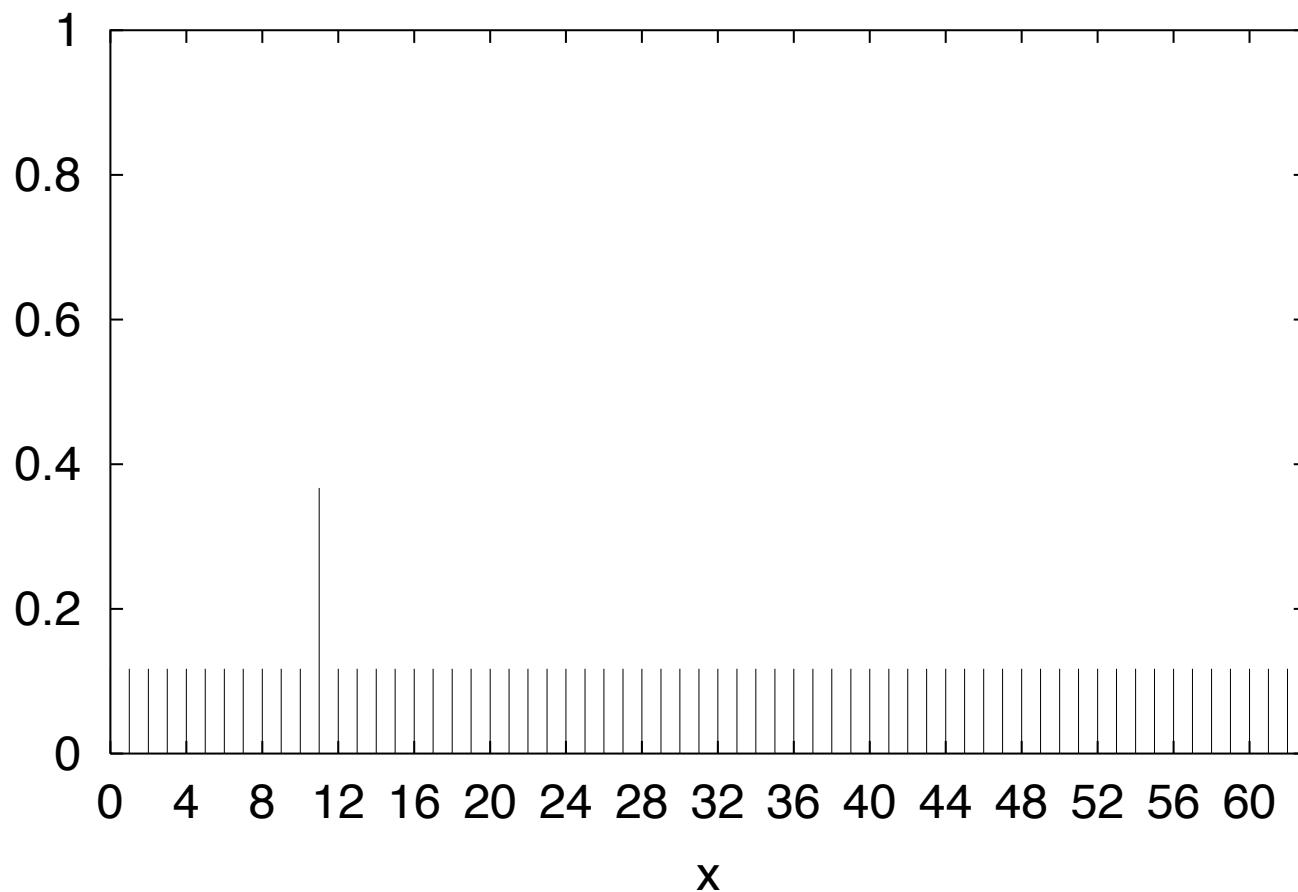
Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

iterative amplitude amplification

iteration 1



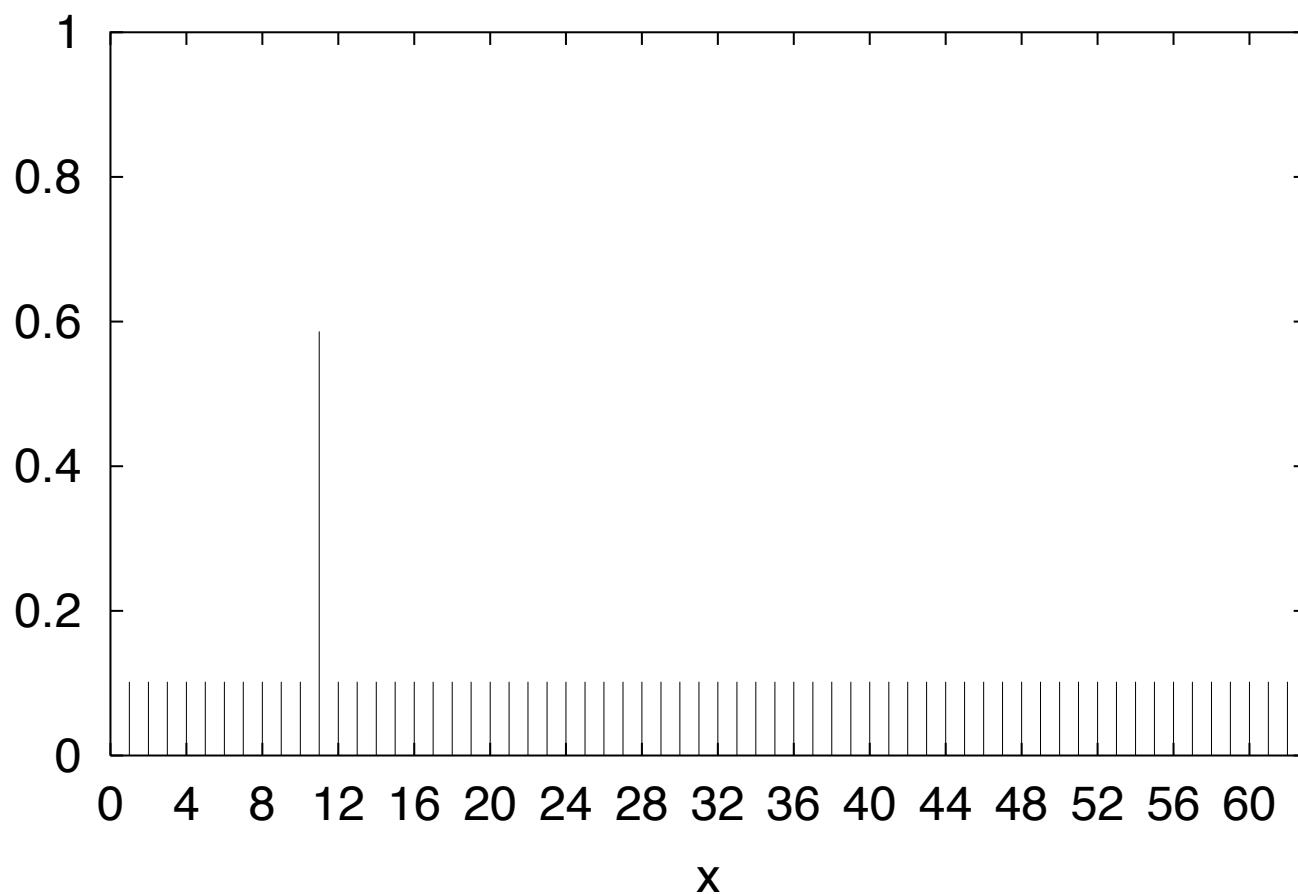
Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

iterative amplitude amplification

iteration 2



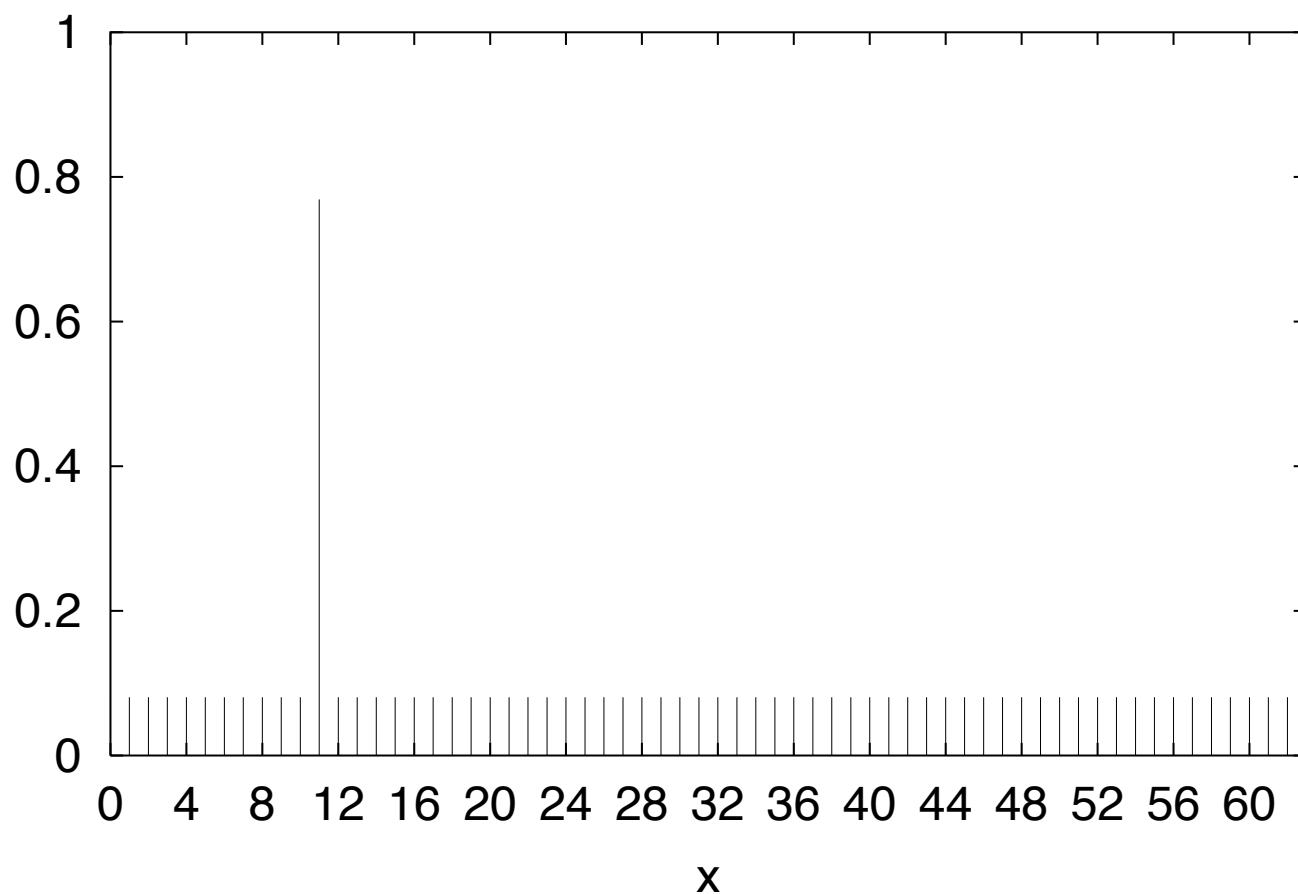
Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

iterative amplitude amplification

iteration 3



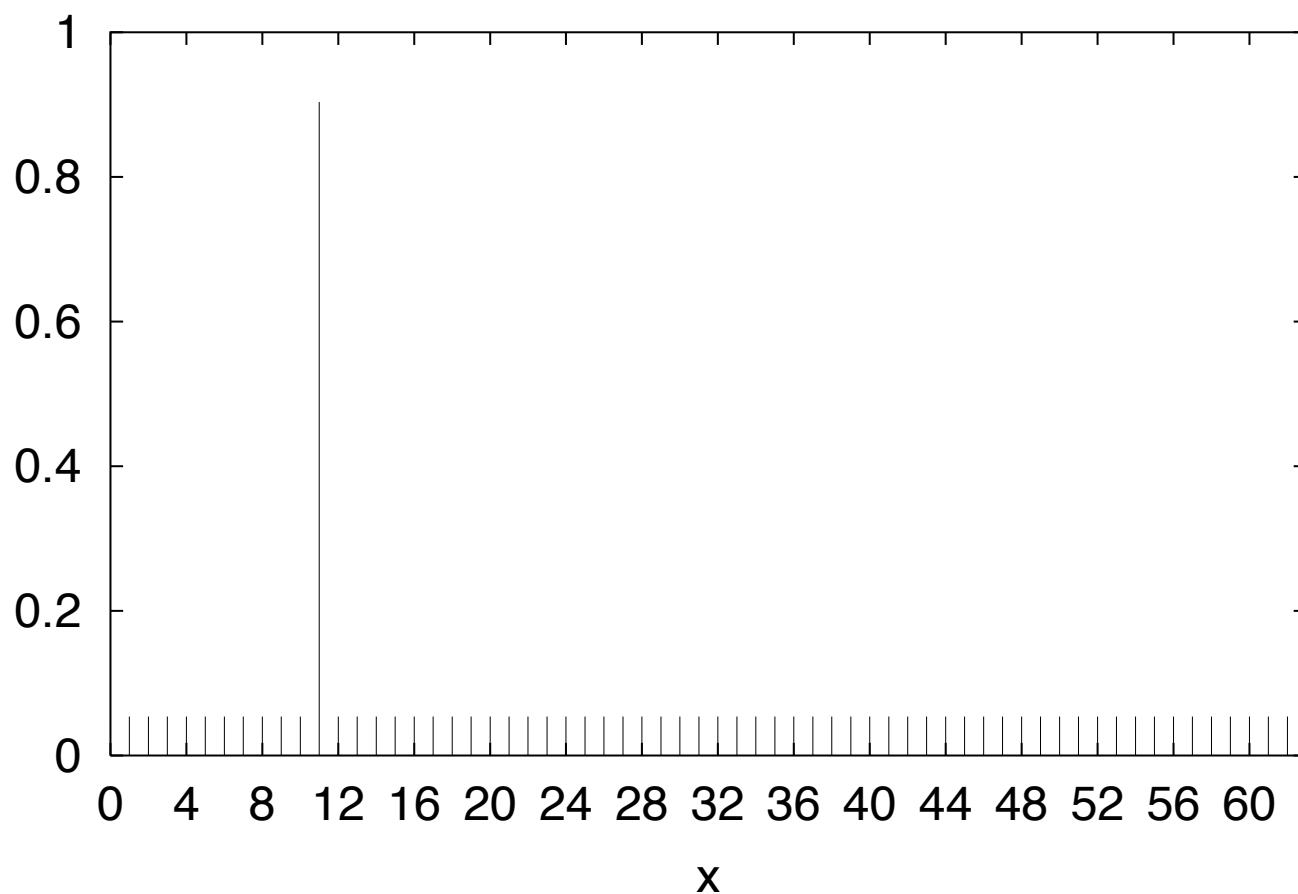
Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

iterative amplitude amplification

iteration 4



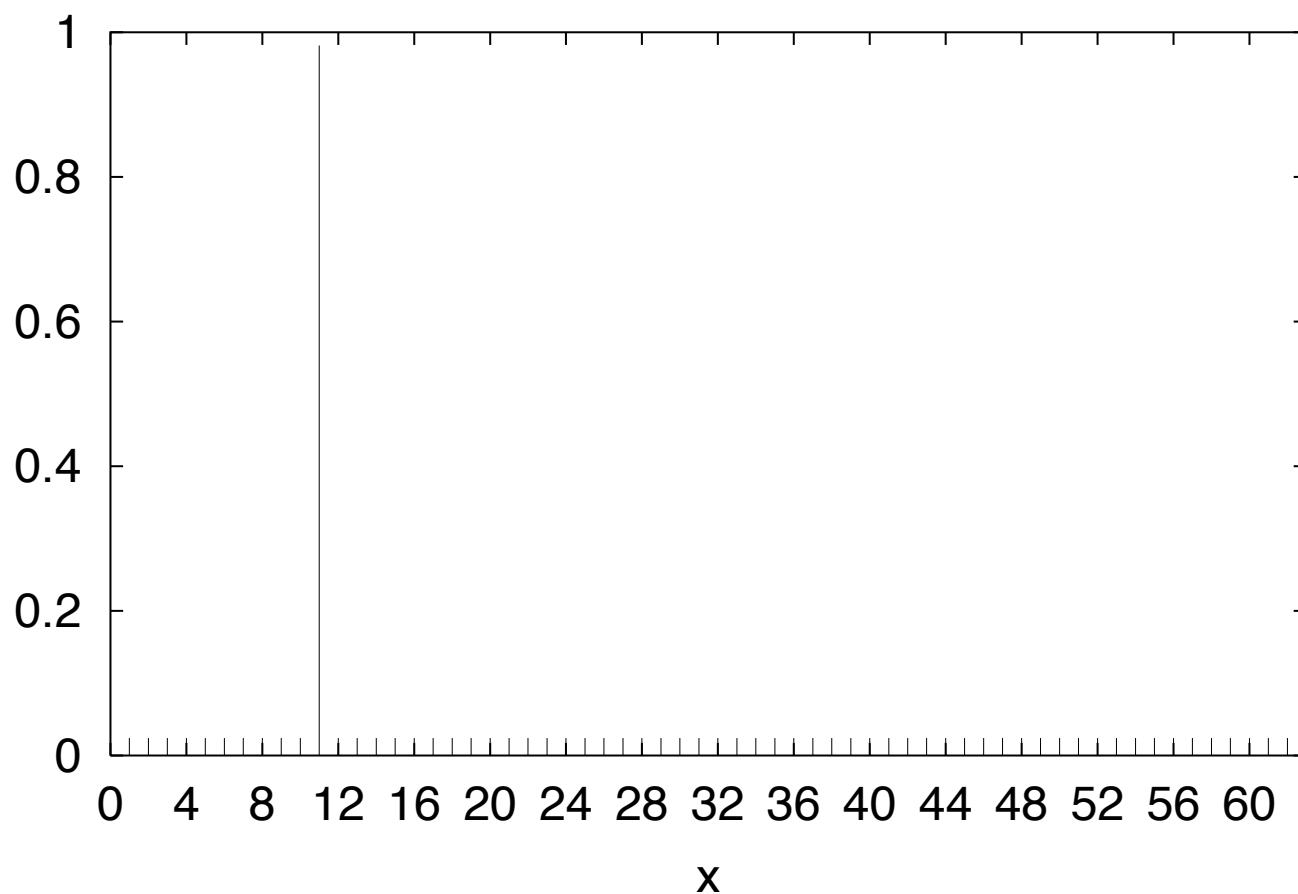
Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

iterative amplitude amplification

iteration 5



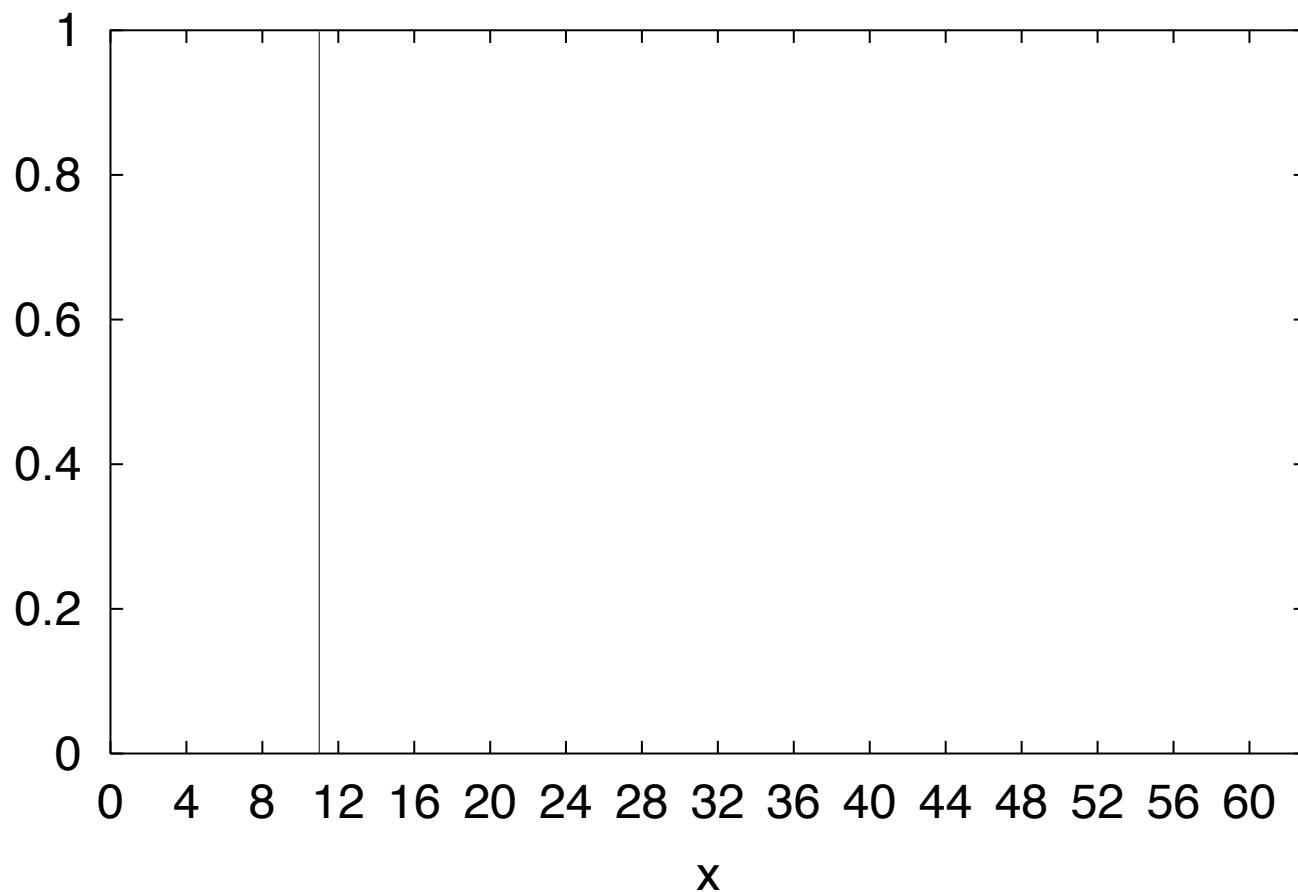
Grover algorithm

reverse lookup

given $f:\{0,1,\dots,2^n-1\} \rightarrow \{0,1\}$ find x with $f(x)=1$

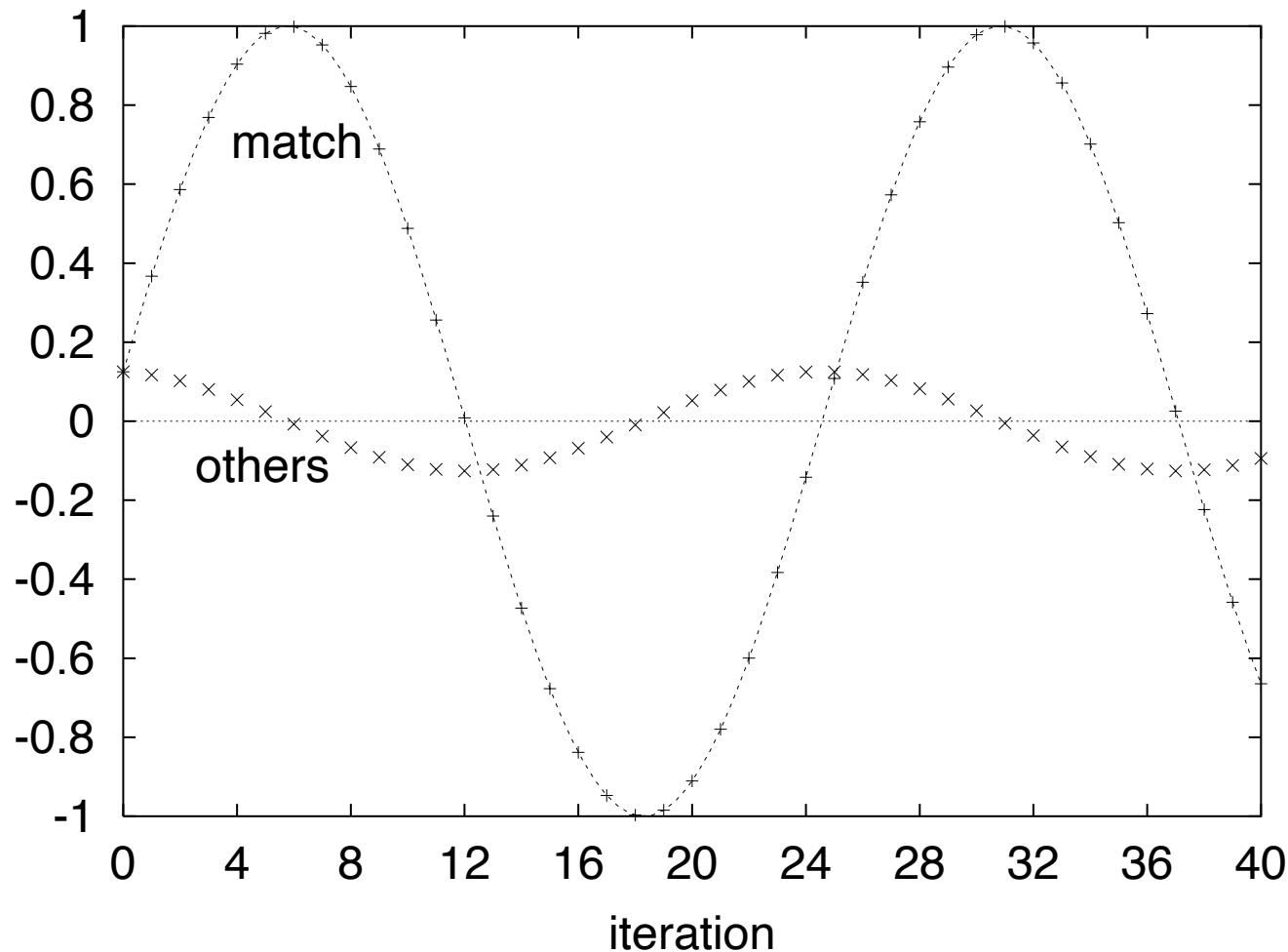
iterative amplitude amplification

iteration 6



Grover algorithm

amplitude for single match: $\sin((2n+1) \arcsin(N^{-1/2}))$



Qbits analog or digital?

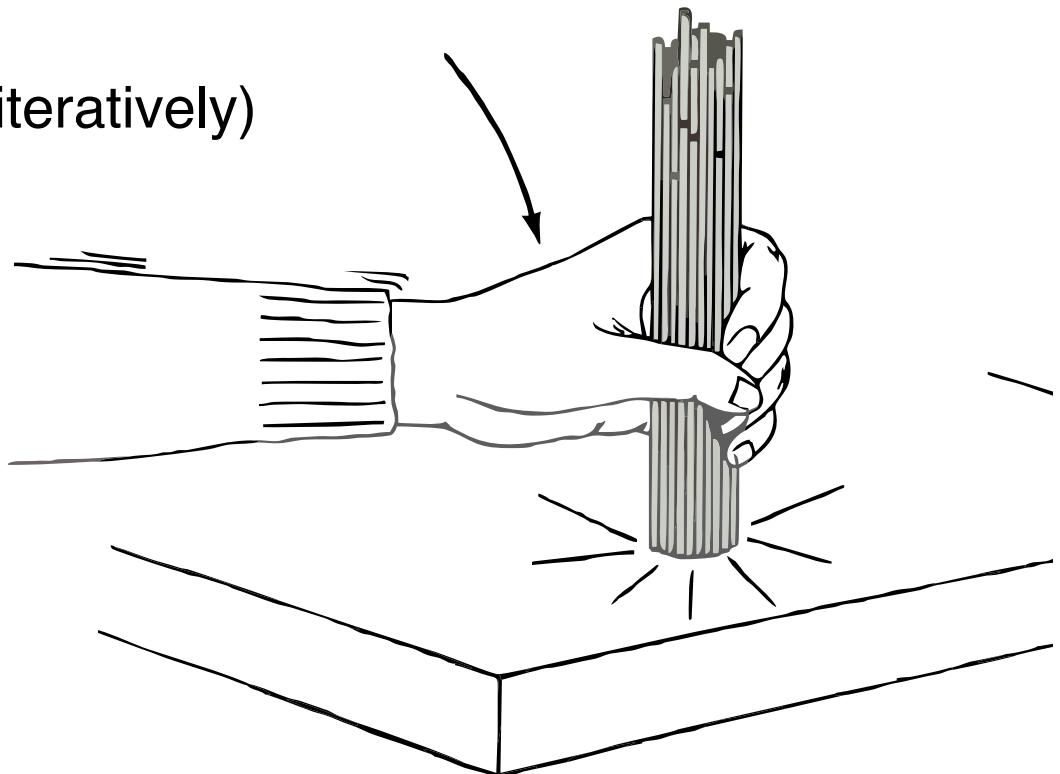
$$|b\rangle = \alpha|0\rangle + \beta|1\rangle \quad \alpha, \beta \in \mathbb{C} \text{ — Qbit analog!?}$$

but: α, β not accessible — measurement returns only 0 or 1

spaghetti computer

A.K. Dewdney, Scientific American 250, 19-26 (June 1984)

- cut (uncooked!) spaghetti to length of numbers
- tap them on table
- pick tallest spaghetti (iteratively)
- gives sorted numbers



$O(N)$ — faster than QuickSort $O(N \log(N))$

Qbits analog or digital?

$$|b\rangle = \alpha|0\rangle + \beta|1\rangle \quad \alpha, \beta \in \mathbb{C} \text{ — Qbit analog!?}$$

but: α, β not accessible — measurement returns only 0 or 1

error correction possible — digital!

idea: bit errors can be described by Pauli matrices:
(discrete errors)

\mathbf{I} — no error

σ_x — bit-flip

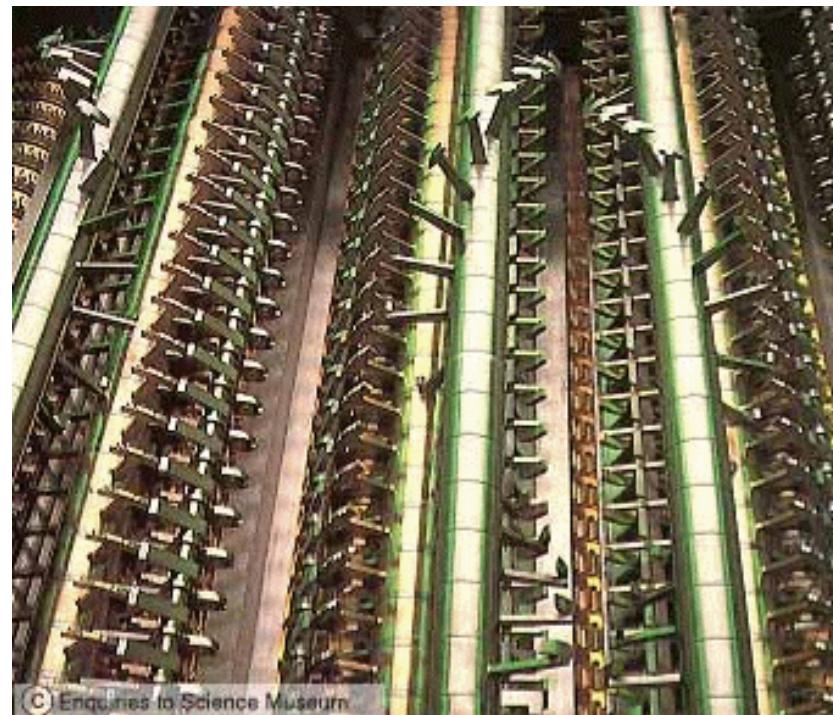
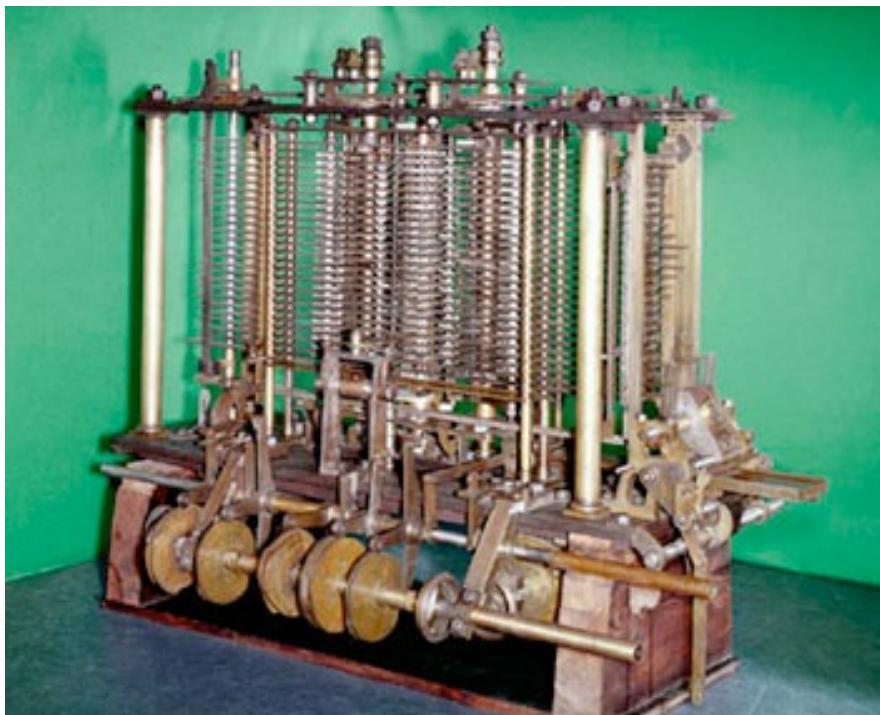
σ_z — phase-flip

σ_y — bit-&phase-flip

project on one of the four error states and correct

inappropriate hardware

mechanical computers

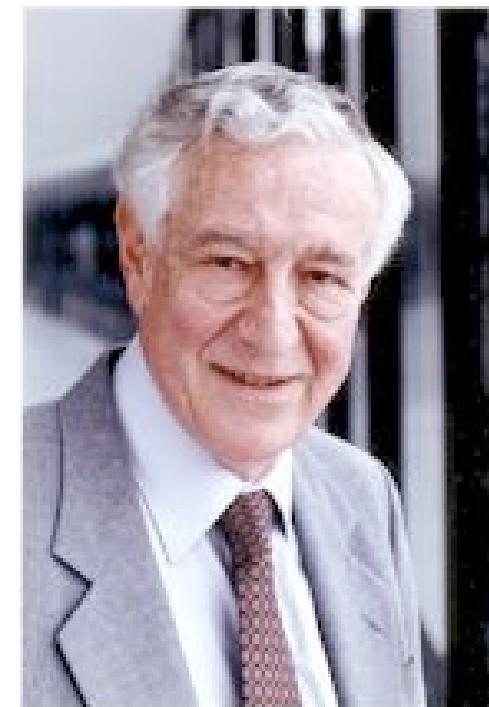


Charles Babbage: Analytical Engine (1834)

Landauer's Disclaimer

Nature 400, 720 (1999)

This proposal, like all proposals for quantum computation, relies on speculative technology, does not in its current form take into account all possible sources of noise, unreliability and manufacturing error, and probably will not work.



Quantum Cryptography



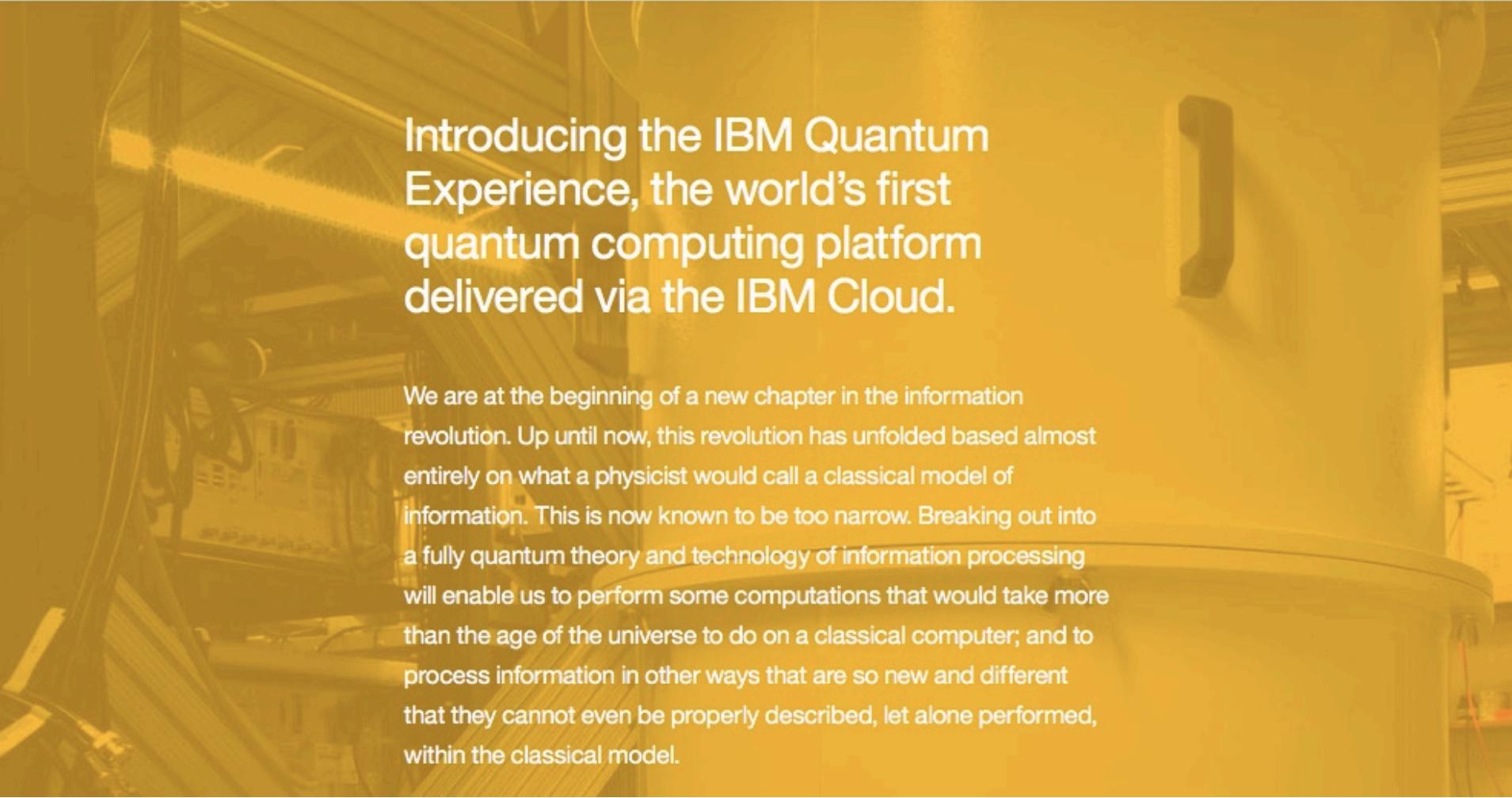
MagiQ: www.magiqtech.com
id quantique: www.idquantique.com

Figure 3: id Quantique's system exchanged keys over 67 km of standard optical fiber.

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We are at the beginning of a new chapter in the information revolution. Up until now, this revolution has unfolded based almost entirely on what a physicist would call a classical model of information. This is now known to be too narrow. Breaking out into a fully quantum theory and technology of information processing will enable us to perform some computations that would take more than the age of the universe to do on a classical computer; and to process information in other ways that are so new and different that they cannot even be properly described, let alone performed, within the classical model.

<https://quantum-computing.ibm.com>

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IBM Quantum Computing Quantum Experience Preview Account Logout

Standard User, Units: 11

← Back to the User Guide

Name: ' Grover N=2 A=10'

Real Quantum Processor

Quantum circuit diagram:

```
Q0 |0> ─────────────────────────────────────────────────────────────────────────
Q1 |0> H ─ S ─ ┌───┐ ─ S ─ H ─ X ─ ┌───┐ ─ X ─ H ─ ┌───┐
Q2 |0> H ─ ┌───┐ H ─ + ─ H ─ ┌───┐ H ─ X ─ H ─ + ─ H ─ X ─ H ─ ┌───┐
Q3 |0> ─────────────────────────────────────────────────────────────────
Q4 |0> ─────────────────────────────────────────────────────────
```

Control qubits: q[1], q[2]

Target qubits: q[1], q[2]

Measurement qubits: q[1], q[2]

Measurement results: h q[1]; h q[2]; s q[1]; h q[2]; cx q[1], q[2]; h q[2]; s q[1]; h q[1]; h q[2]; cx q[1], q[2]; h q[2]; s q[1]; h q[1]; h q[2]; cx q[1], q[2]; h q[2]; x q[1]; x q[2]; h q[2]; cx q[1], q[2]; h q[2]; x q[1]; x q[2]; h q[1]; h q[2]; measure q[1]; measure q[2];

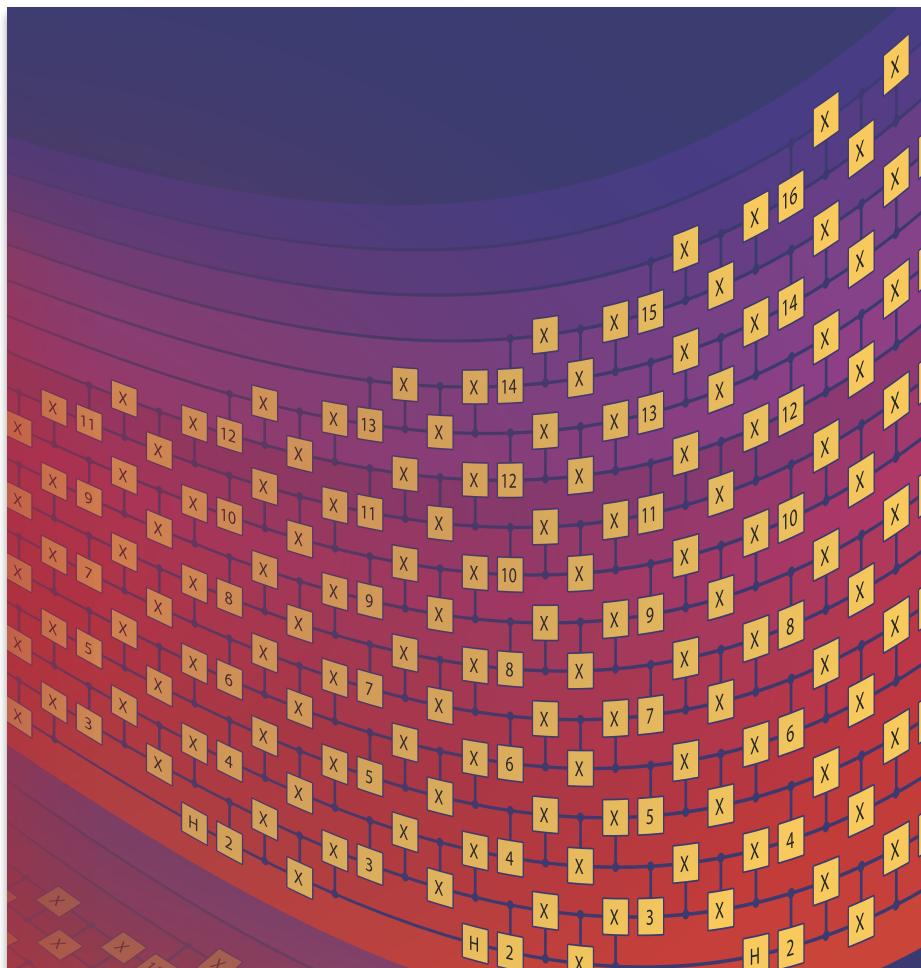
Quantum gates palette:

- Id
- X
- Z
- Y
- H
- S
- S^\dagger
- +
- T
- T^\dagger
- not^z
- Measure

Buttons:

- Simulate
- Run

Simulating Materials



Simulating Correlations with Computers

Eva Pavarini and Erik Koch (Eds.)

www.cond-mat.de/events/correl21

1. Erik Koch
Second Quantization and Jordan-Wigner Representations
2. Klaus Doll
Fundamentals of Quantum Chemistry
3. Kieron Burke
Lies My Teacher Told Me About Density Functional Theory: See
4. Pina Romaniello
Hubbard Dimer in GW and Beyond
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Analog Quantum Simulations of the Hubbard Model
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Programming Quantum Computers
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Quantum Chemistry on Quantum Computers
13. David DiVincenzo
Quantum Computing — Quo Vadis?

quantum computing

- can only solve what classical computers can (*simulatable*) but possibly much faster (*quantum parallelism*)
- Qbits look analog but only *digital* information accessible
- results usually *probabilistic* — best for satisfiability problems
- no *reliable* hardware available yet
- noise, number of Qbits and connectivity matter

Confused?

Möglicherweise ist es, nebenbei gesagt, für die Kopenhagener Interpretation der Quantenmechanik wichtig, dass ihre Sprache in einem gewissen Grad unbestimmt ist, und ich bezweifle, dass sie durch den Versuch, diese Unbestimmtheit zu vermeiden, klarer werden kann.

(W. Heisenberg)

