Quantum Technology:
Putting Weirdness to Use



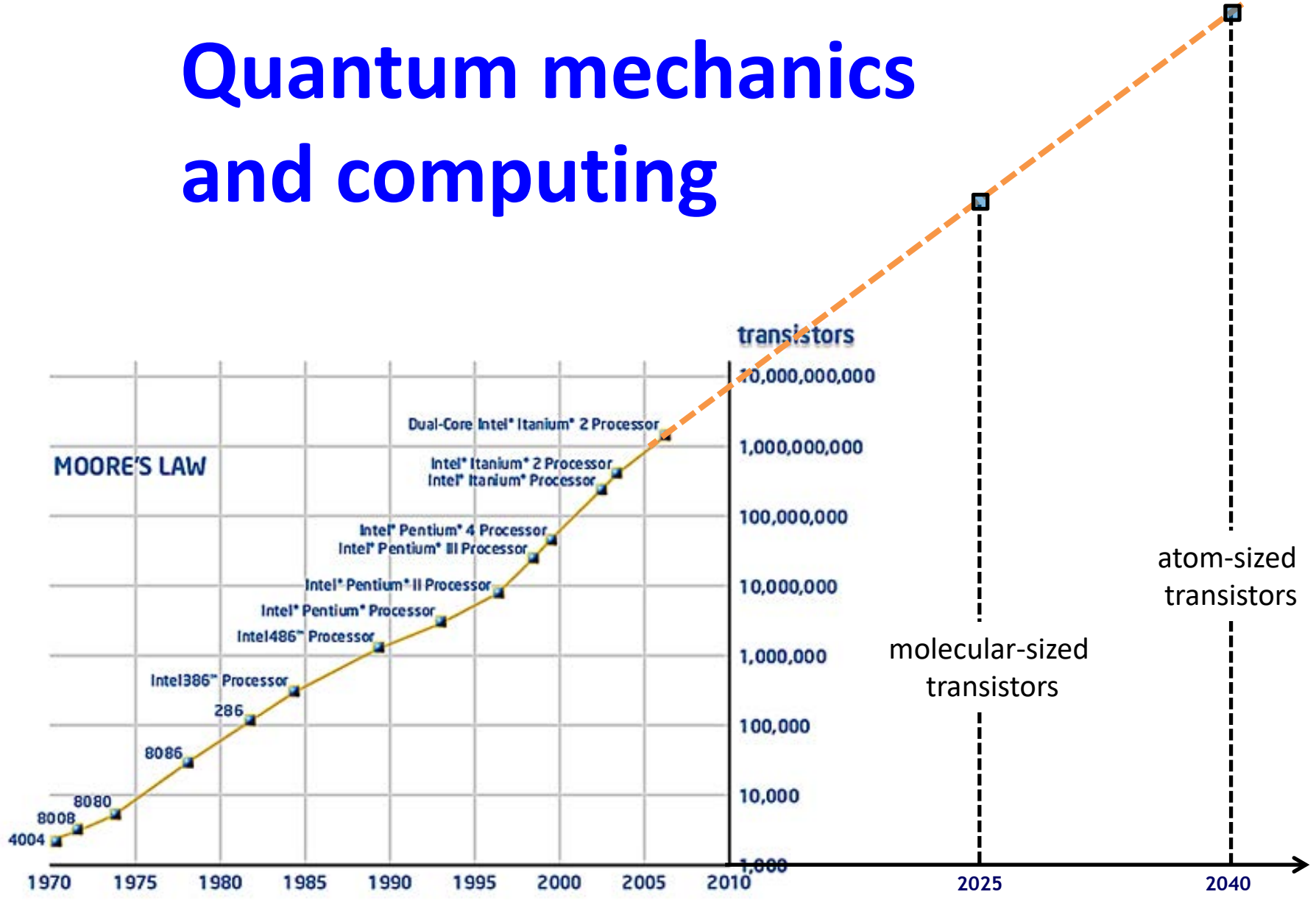
Chris Monroe

University of Maryland
Department of Physics

JOINT QUANTUM INSTITUTE

National Institute of Standards and Technology

Quantum mechanics and computing

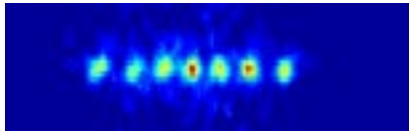


"There's Plenty of Room at the Bottom" (1959)

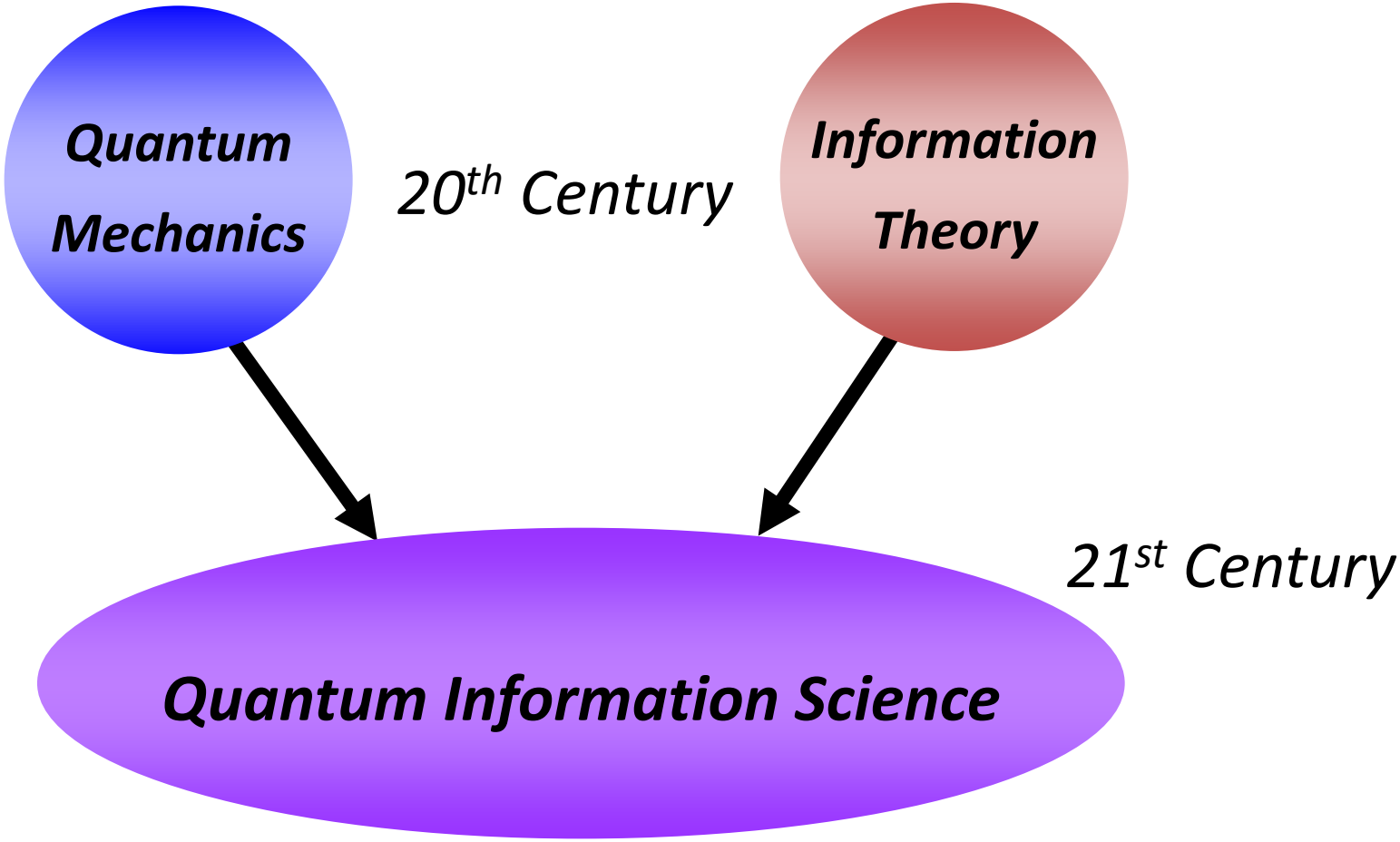


Richard Feynman

"When we get to the very, very small world – say circuits of seven atoms - we have a lot of new things that would happen that represent completely new opportunities for design. ***Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics…***"



A new science for the 21st Century?



Computer Science and Information Theory

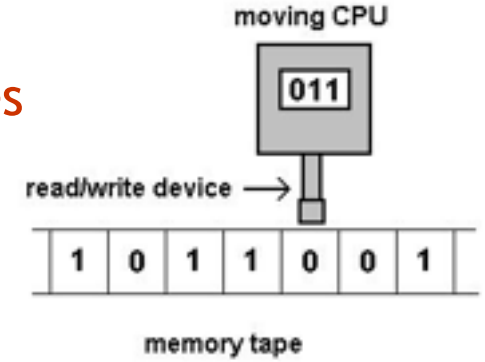


Charles Babbage (1791-1871)
mechanical difference engine





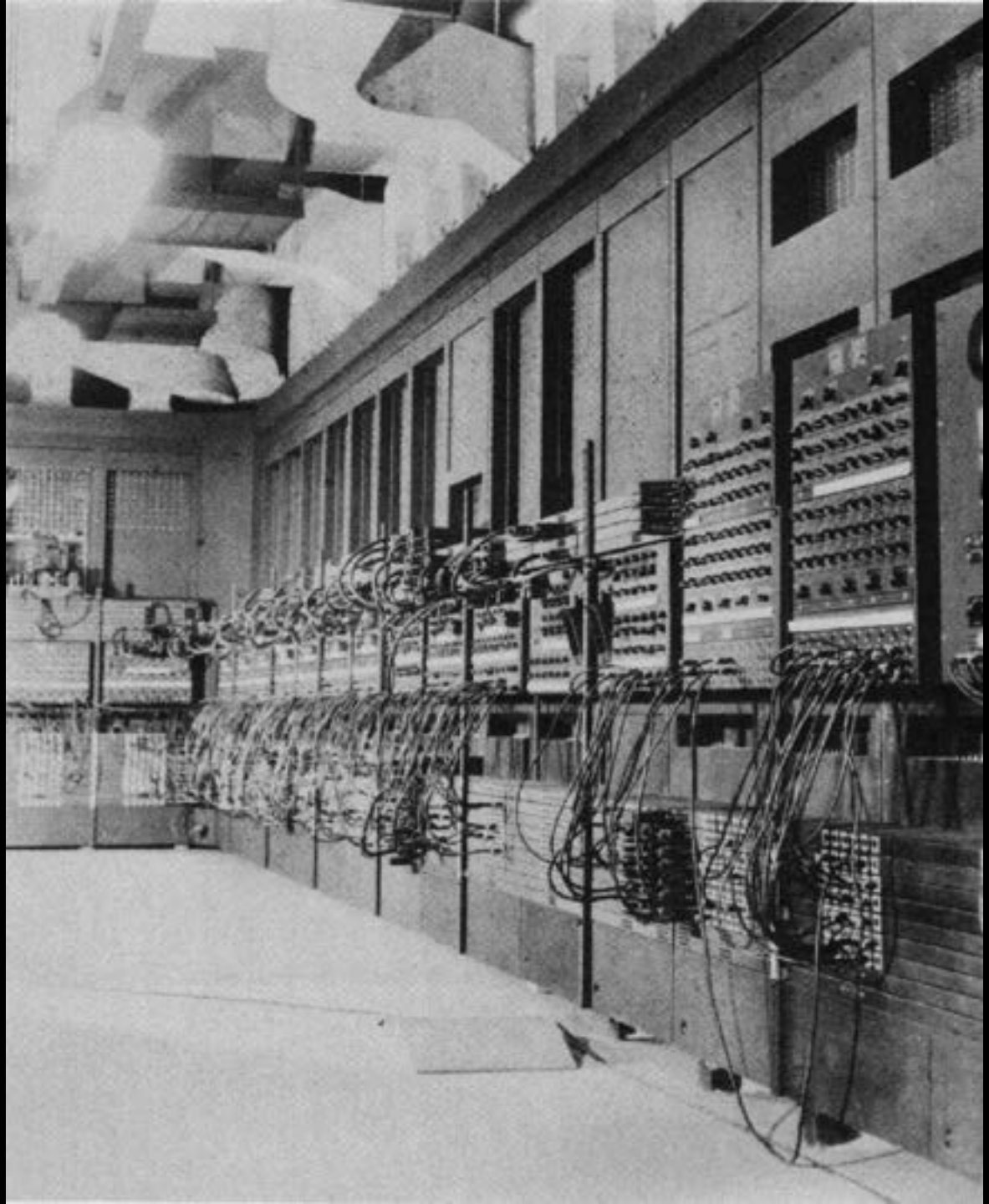
Alan Turing (1912-1954)
universal computing machines





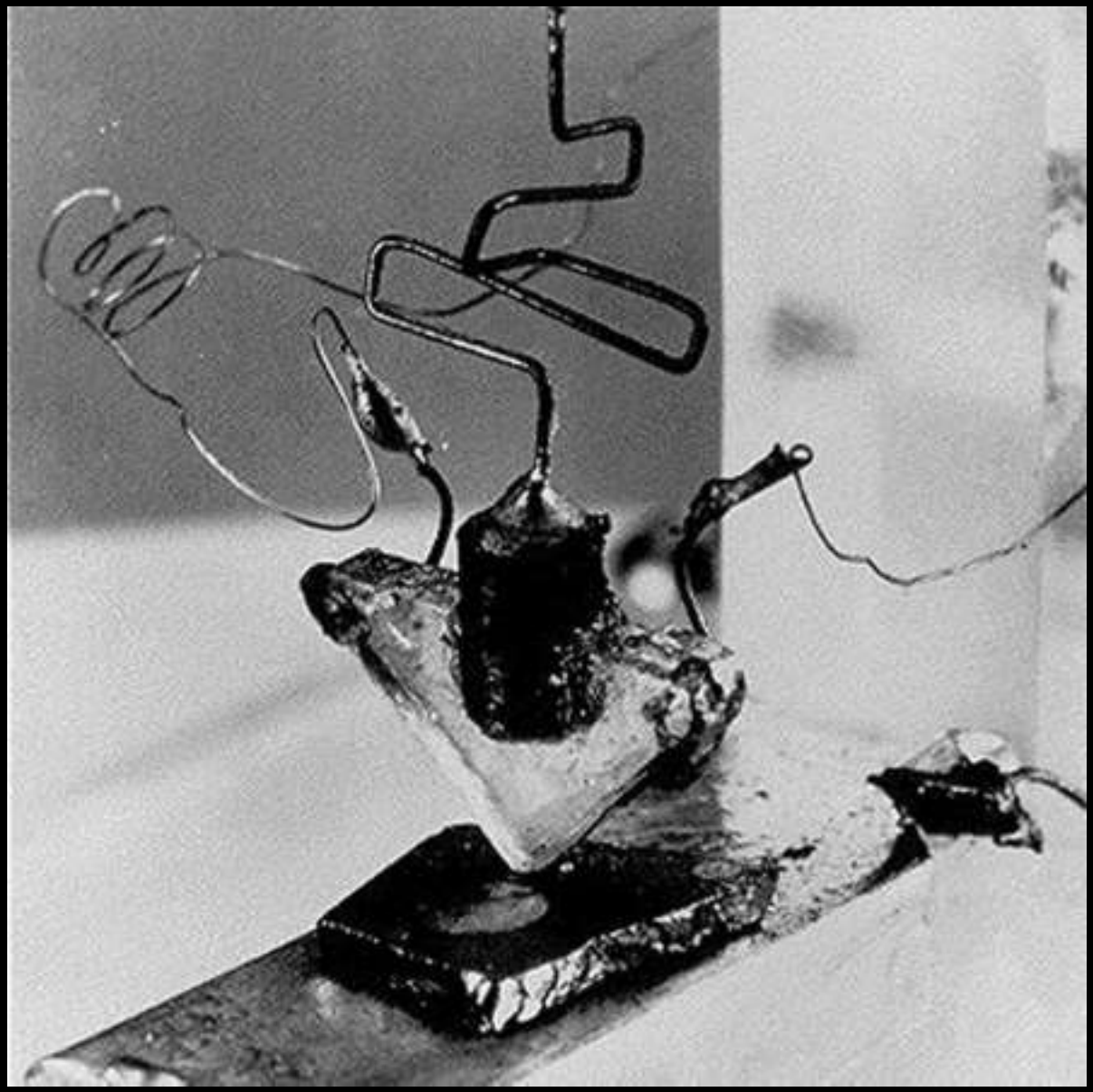
Claude Shannon (1916-2001)
quantify information: the bit

$$H = -\sum_{i=1}^{k} p_i \log_2 p_i$$



ENIAC
(1946)





The first solid-state transistor
(Bardeen, Brattain & Shockley, 1947)

Quantum Mechanics: A 20th century revolution in physics

- Why doesn't the electron collapse onto the nucleus of an atom?
- Why are there thermodynamic anomalies in materials at low temperature?
- Why is light emitted at discrete colors?
- . . . .



Albert Einstein (1879-1955)



Werner Heisenberg (1901-1976)

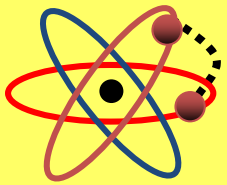


Erwin Schrödinger (1887-1961)

The Golden Rules of Quantum Mechanics

Rule #1: *Quantum objects are waves and can be in states of superposition.*

"qubit": $|0\rangle$ ***and*** $|1\rangle$



Rule #2: *Rule #1 holds as long as you don't look!*



$|0\rangle$ ***and*** $|1\rangle$

or

$|0\rangle$ $|1\rangle$

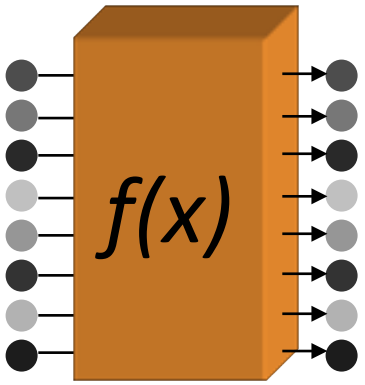
probability p $1-p$

GOOD NEWS…

quantum parallel processing on 2^N inputs

Example: N=3 qubits

$$\Psi = a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle$$
$$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$$

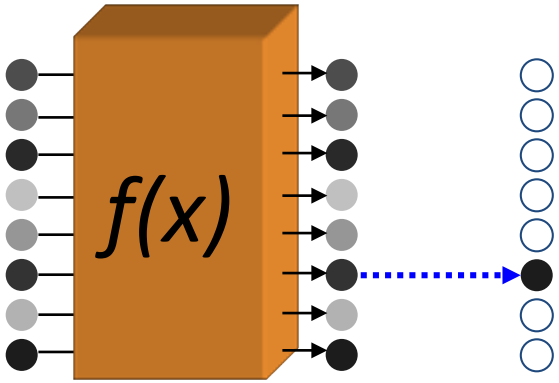


N=300 qubits: more information than particles in the universe!

…BAD NEWS…

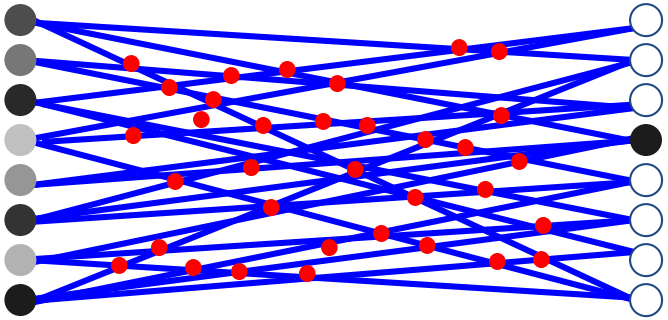
Measurement gives random result

e.g., $\Psi \Rightarrow |101\rangle$



…GOOD NEWS!

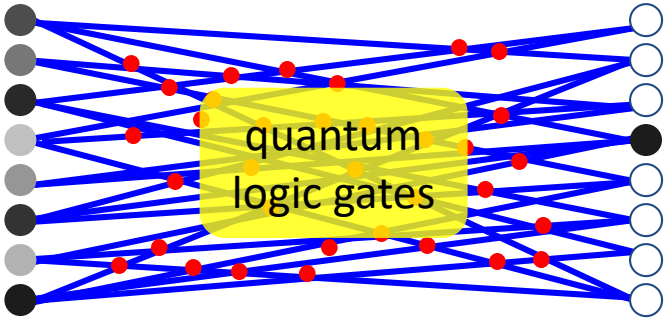
quantum interference



depends on
all inputs

…GOOD NEWS!

quantum interference



depends on
all inputs

quantum $\sqrt{\text{NOT}}$ gate:

$$|0\rangle \rightarrow |0\rangle + |1\rangle$$
$$|1\rangle \rightarrow |1\rangle - |0\rangle$$

quantum XOR gate:

$$|0\rangle\,|0\rangle \rightarrow |0\rangle\,|0\rangle$$
$$|0\rangle\,|1\rangle \rightarrow |0\rangle\,|1\rangle$$
$$|1\rangle\,|0\rangle \rightarrow |1\rangle\,|1\rangle$$
$$|1\rangle\,|1\rangle \rightarrow |1\rangle\,|0\rangle$$

e.g., $(|0\rangle + |1\rangle)\,|0\rangle \rightarrow |0\rangle|0\rangle + |1\rangle|1\rangle$

superposition → ***entanglement***

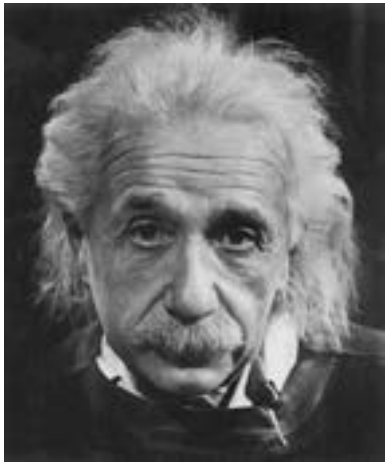
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.



Quantum State: [0][0] & [1][1]



John Bell (1964)

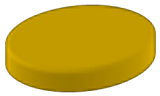
Any possible "completion" to quantum mechanics will violate local realism just the same

Entanglement: Quantum Coins

Two coins in a quantum superposition

[H][H] & [T][T]

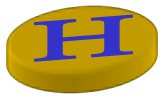
1





1



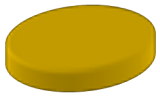


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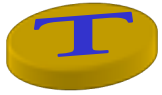
1
0





1
0



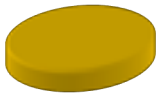


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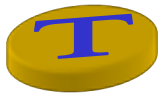
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1
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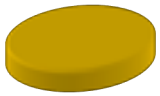


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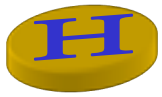
1
0
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1





1
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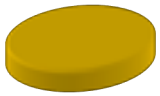


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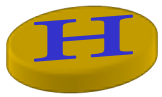
1
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1





1
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0
1
1

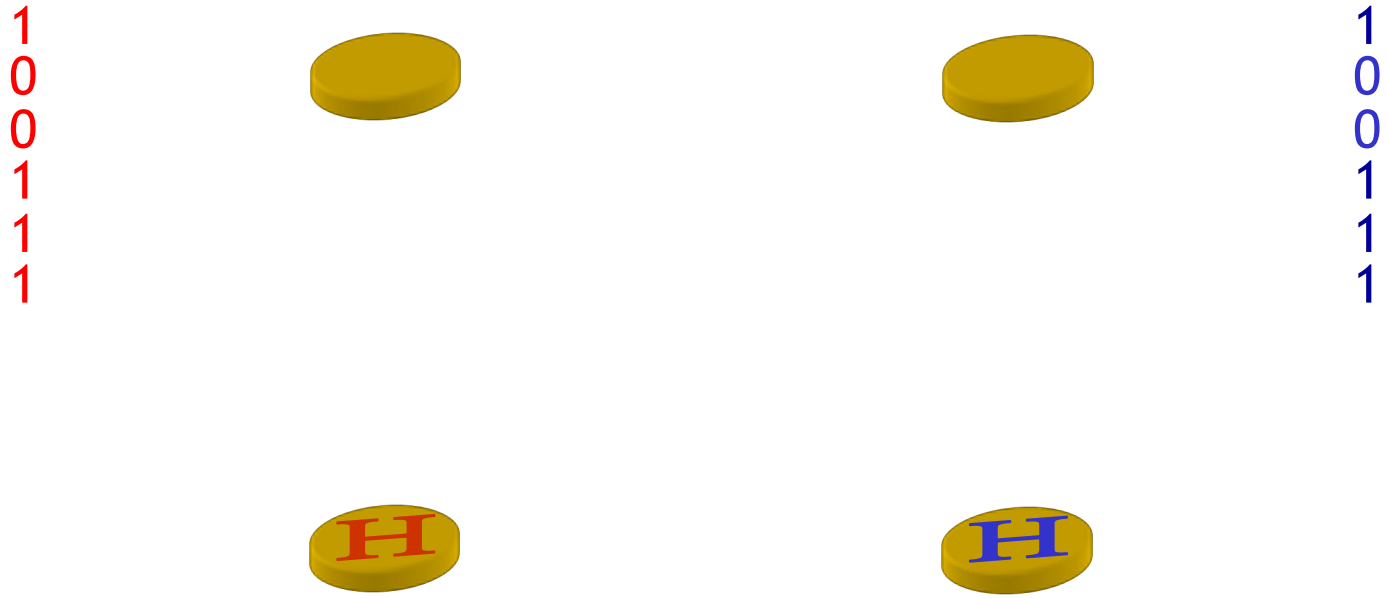




Entanglement: Quantum Coins

Two coins in a quantum superposition

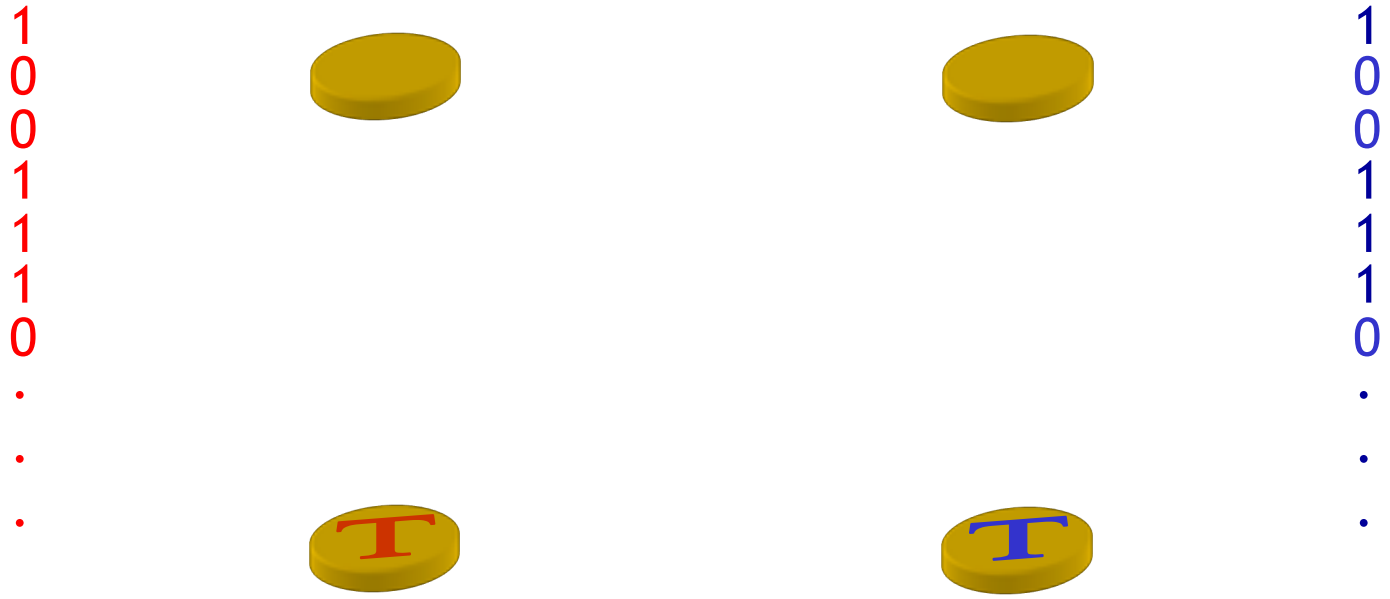
[H][H] & [T][T]



Entanglement: Quantum Coins

Two coins in a quantum superposition

[H][H] & [T][T]



Application: quantum cryptographic key distribution

```
  01011100   plaintext
+ 11001010   KEY
----------
  10010110   ciphertext
```

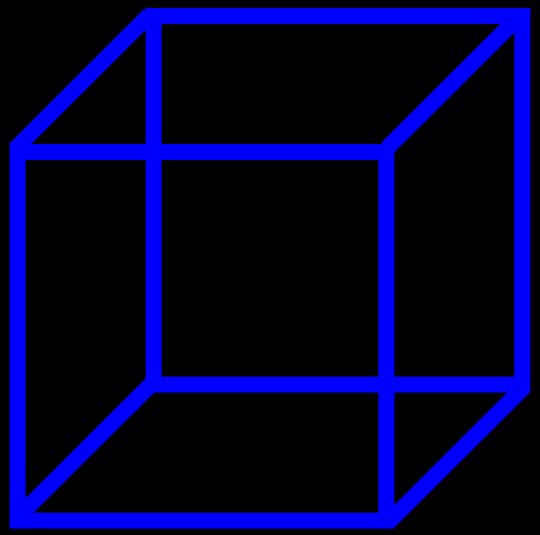


10010110



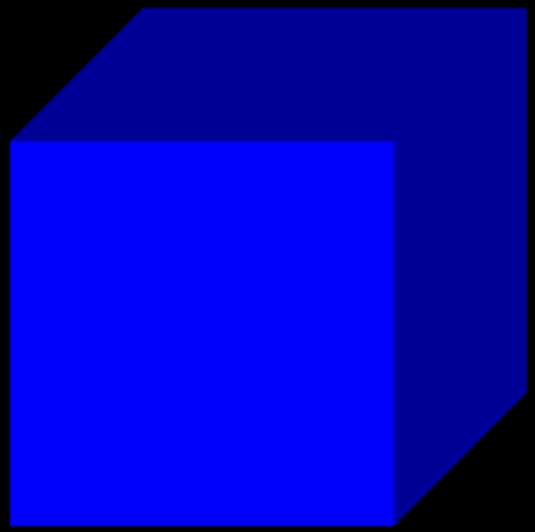
```
ciphertext   10010110
       KEY + 11001010
----------------------
 plaintext   01011100
```

Quantum Superposition



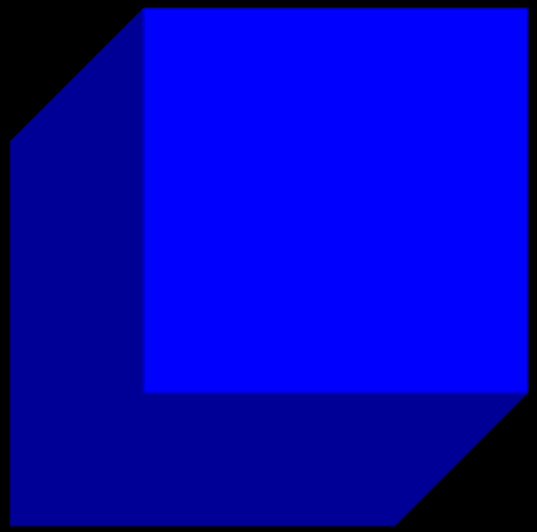
From Taking the Quantum Leap, by Fred Alan Wolf

Quantum Superposition



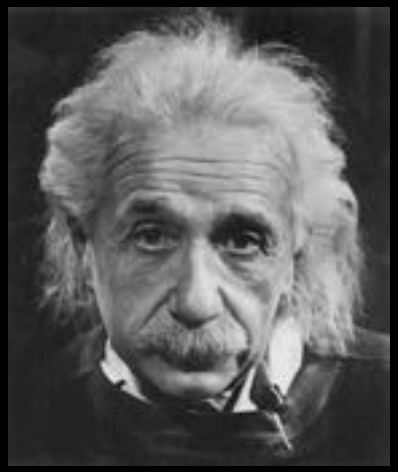
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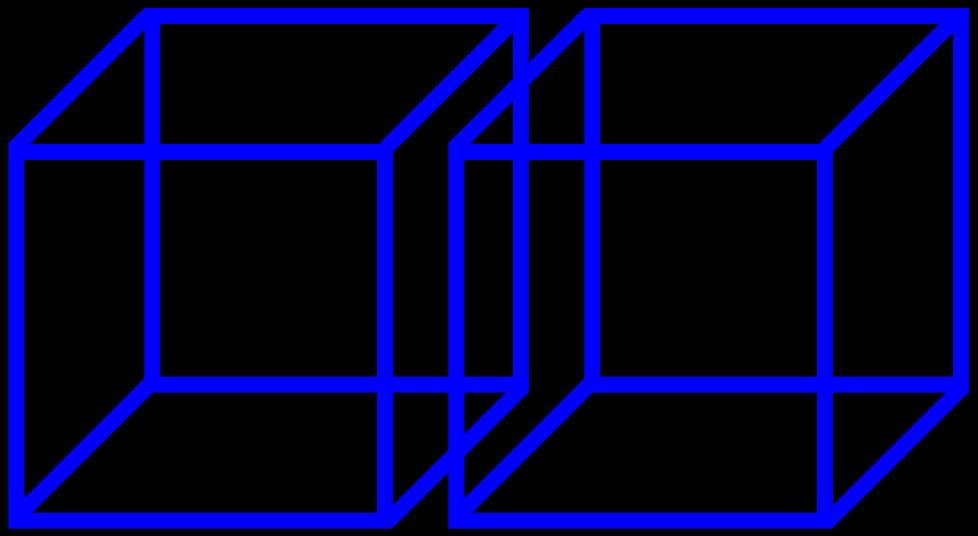


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Quantum Entanglement

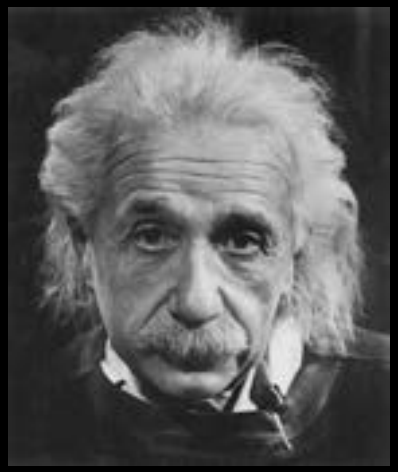


"Spooky action-at-a-distance"
(A. Einstein)

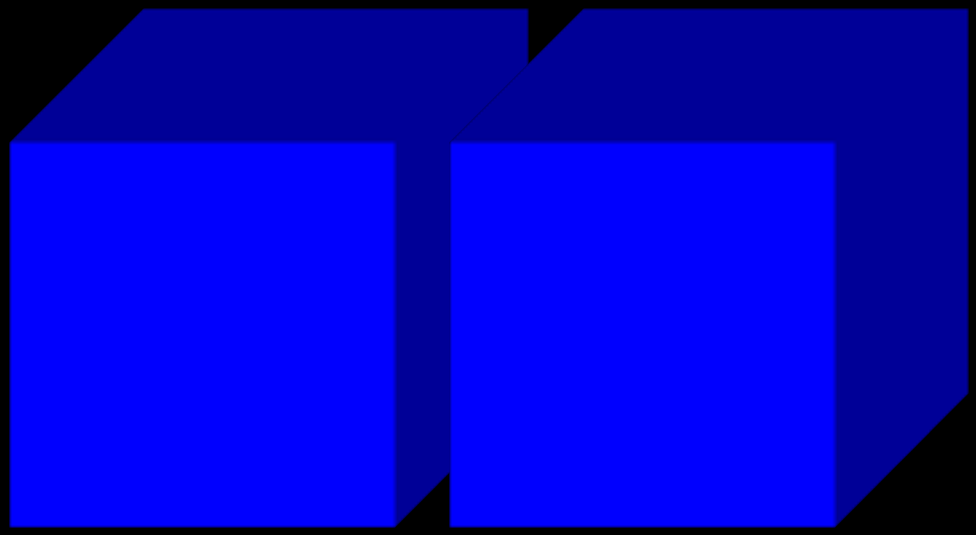


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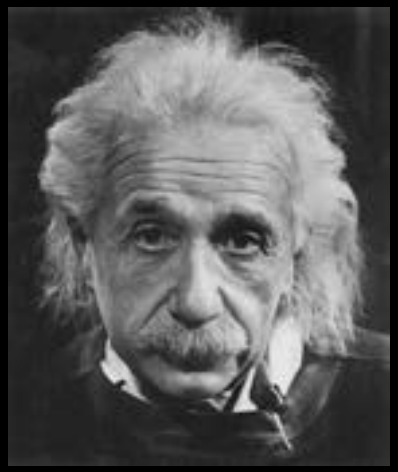


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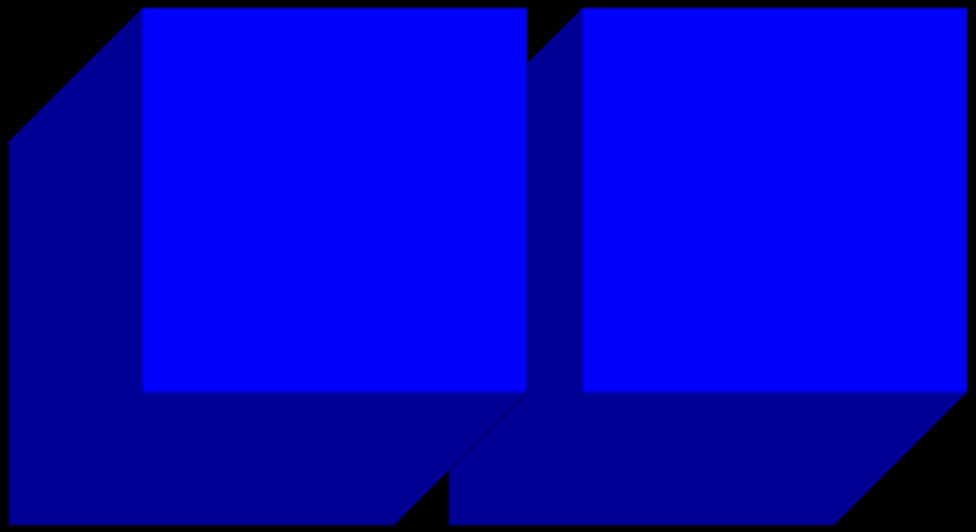


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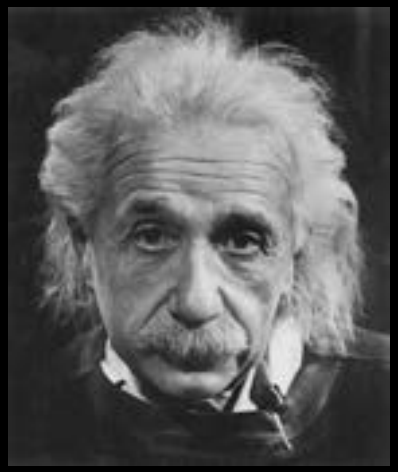


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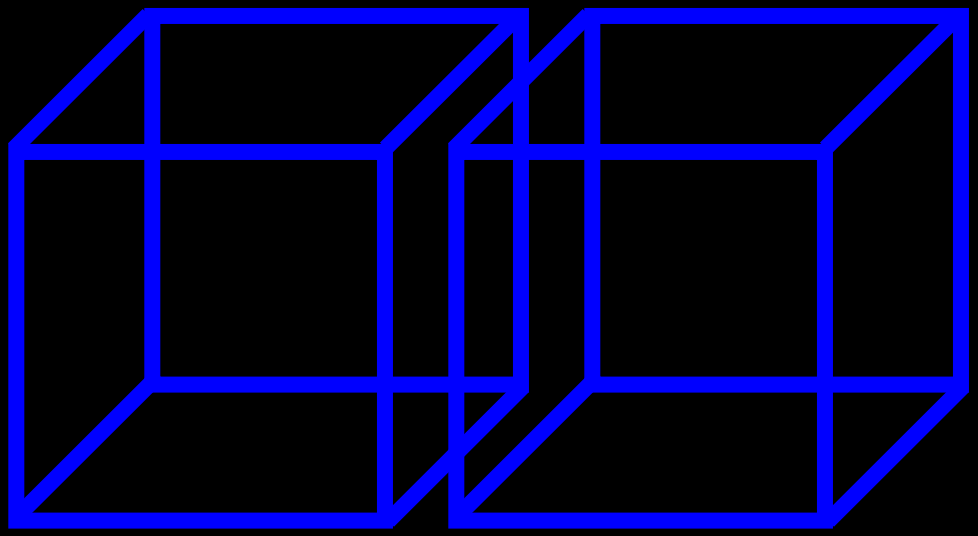


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Quantum Entanglement



"Spooky action-at-a-distance"
(A. Einstein)



From Taking the Quantum Leap, by Fred Alan Wolf



David Deutsch

"When a quantum measurement is made, the universe bifucates!"

- Many Universes
- Multiverse
- Many Worlds

THE QUANTUM SOCIETY

Mind, Physics, and a New Social Vision

DANAH ZOHAR
& IAN MARSHALL

William Morrow and Company, Inc. • New York

both aspects of some larger whole that naturally keeps them in synchrony. For Einstein, this made no sense. In his Theory of Hidden Variables, he said that there must be some mysterious common factor which accounted for all the similarities. In the analogy of the twins, this might be our shared genetic material. The controversy wore on for years, but was eventually settled by Irish physicist John Bell. His theorem—Bell's Theorem—led to experiments that finally settled the matter.

If we applied Bell's Theorem to my twin and myself, we would look for some instantaneous correlation in our lives that couldn't possibly be accounted for by genetics. Imagine, for example, that I decide to enroll in a dance class in Oxford. My twin, too, might be observed to enroll in such a class in New York, at exactly the same time. Strange, but perhaps not absolutely outside some genetic predisposition linked with coincidence.

But supposing that I am observed to raise one or the other of my arms during the exercises. What does my twin do? If quantum physics is right, and important aspects of our lives are indeed instantaneously correlated, she should raise one of her arms (the opposite one) at exactly the same moment. If Einstein is right, my raising an arm should make no difference to what she does—no shared genetic material can account for simultaneous arm raising, and no faster-than-light signal can travel from Oxford to New York to tell my twin what I have done.

In fact, if we are quantum twins, every time I am seen to raise my right arm, my twin raises her left one. If I raise my left arm, she raises her right one, at exactly the same moment. Which arm I raise at any time is completely indeterminate—both my twin and I are fully ambidextrous. Each of us chooses freely which arm to raise in the dance. And yet our behavior is linked as though we are standing in the same room and there are springs connecting our arms. Instantaneous, nonlocal correlations may be "ghostly and absurd," but they are a fact of quantum reality.

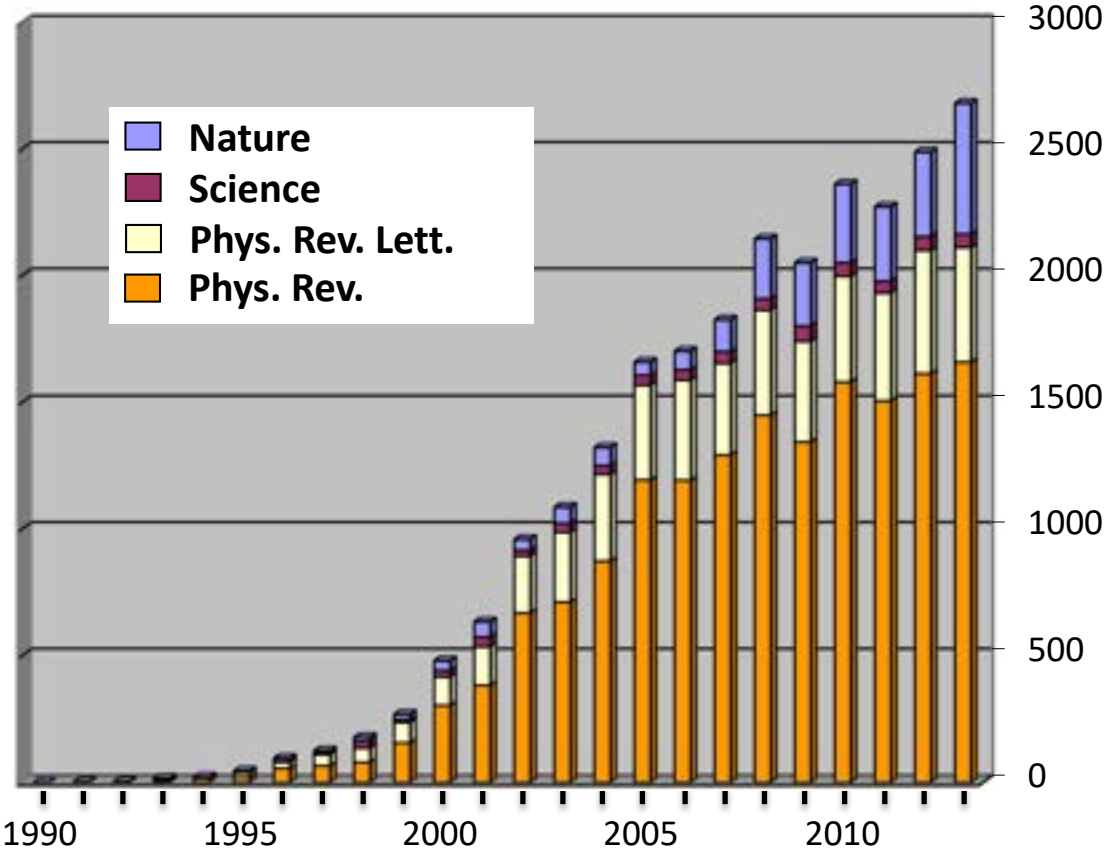
In social reality, too, there often seems to be an eerie correlation between apparently separate events or situations—the spontaneous appearance of revolutions or the acceptance of new practices all over the globe, or the almost simultaneous discovery of creative ideas by two or more people working in ignorance of

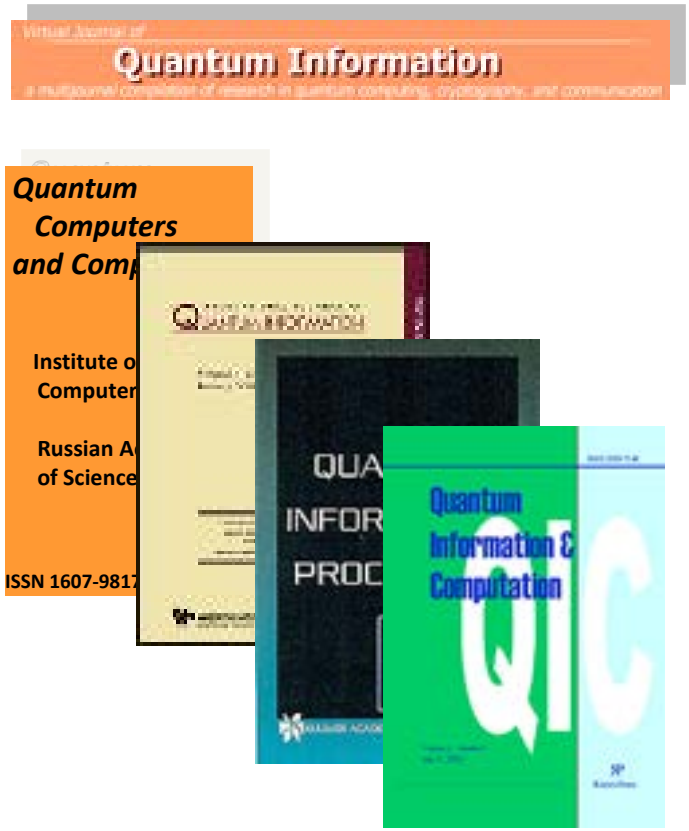
David Deutsch (1985)

Peter Shor (1994) fast number factoring $N = p \times q$

Lov Grover (1996) fast database search

 # articles mentioning "Quantum Information" or "Quantum Computing"





Quantum Factoring

P. Shor, SIAM J. Comput. **26**, 1474 (1997)
A. Ekert and R. Jozsa, Rev. Mod. Phys. **68**, 733 (1996)

Look for a *joint property* of all 2^N inputs
e.g.: the periodicity of a function

$$f(x) = \sin\left(2\pi \frac{x}{p}\right) \qquad p = \text{period}$$

$$f_a(x) = a^x (Mod\ N) \qquad r = \text{period}\ (a = \text{parameter})$$

x	2^x	2^x (Mod 15)
0	1	1
1	2	2
2	4	4
3	8	8
4	16	1
5	32	2
6	64	4
7	128	8
8	256	1

etc…

A quantum computer can factor numbers exponentially faster than classical computers

$$15 = 3 \times 5$$

$$3864788462100938762143232563 1 = ? \times ?$$

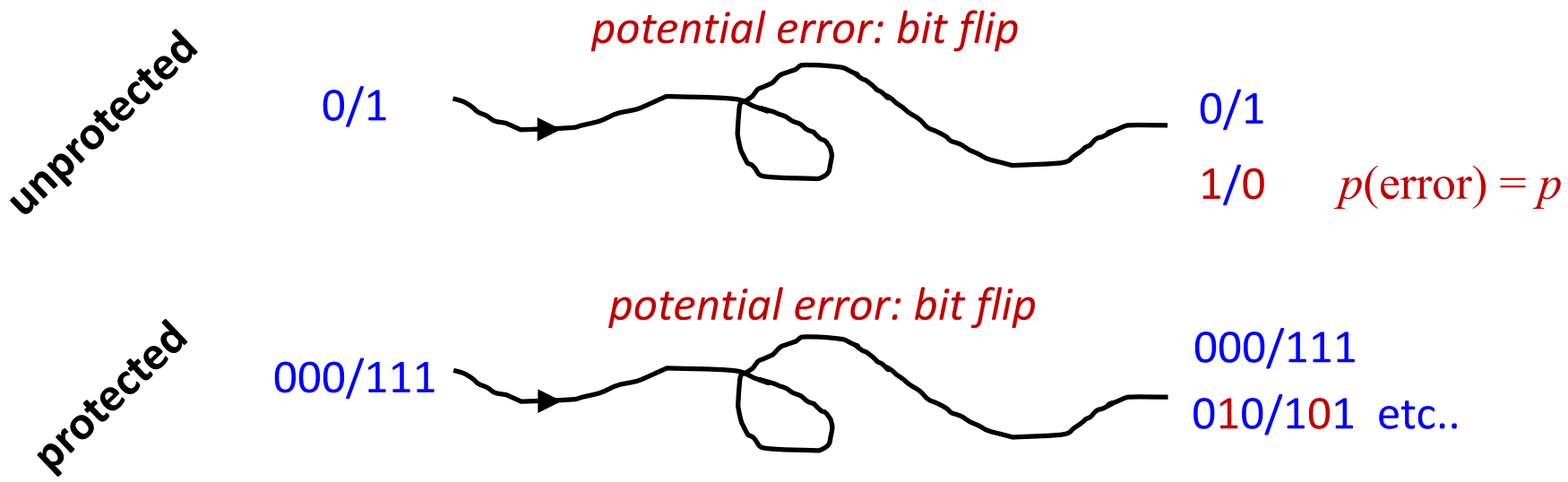
application: cryptanalysis $(N \sim 10^{200})$



Error-correction

Shannon (1948)

Redundant encoding to protect against (rare) errors



take majority

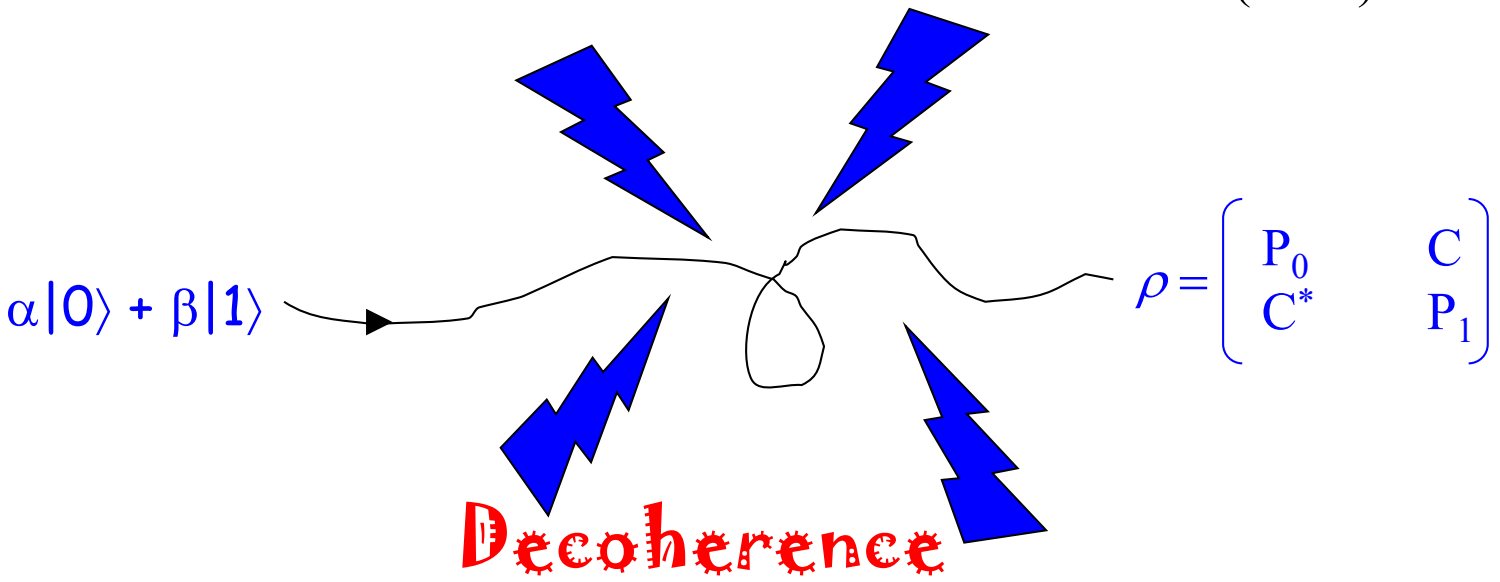
$$p(error) = 3p^2(1-p) + p^3$$

$$p \to 3p^2(1-p) + p^3$$

better off whenever $p < 1/2$

Quantum error-correction

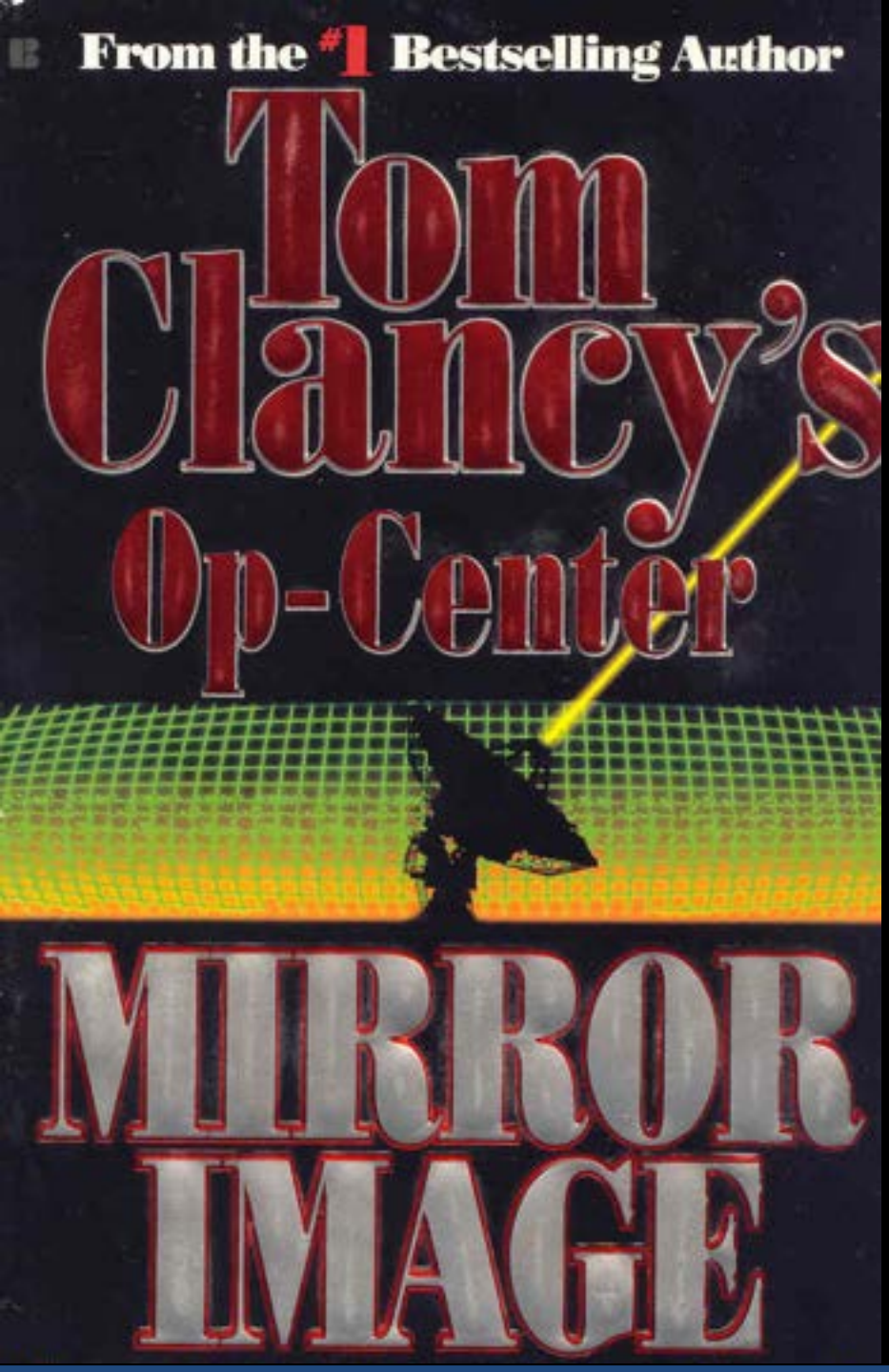
Shor (1995)
Steane (1996)



$$\alpha|0\rangle + \beta|1\rangle \Rightarrow \quad \alpha/4\{\ |00000\rangle + |10010\rangle + |01001\rangle + |10100\rangle$$
$$+|01010\rangle - |11011\rangle - |00110\rangle - |11000\rangle$$
$$-|11101\rangle - |00011\rangle - |11110\rangle - |01111\rangle$$
$$-|10001\rangle - |01100\rangle - |10111\rangle + |00101\rangle\ \}$$

$$+\ \beta/4\{\ |11111\rangle + |01101\rangle + |10110\rangle + |01011\rangle$$
$$+|10101\rangle - |00100\rangle - |11001\rangle - |00111\rangle$$
$$-|00010\rangle - |11100\rangle - |00001\rangle - |10000\rangle$$
$$-|01110\rangle - |10011\rangle - |01000\rangle + |11010\rangle\ \}$$

5-qubit code
corrects all
1-qubit errors
to first order



by executives doing surprisingly little. Psychologist Liz Gordon was chewing nicotine gum in the smoke-free room, nervously twirling a lock of short brown hair, sipping her dark coffee with three sugars and reading the new week's supermarket tabloids.

Operations Support Officer Matt Stoll was playing poker with Environmental Officer Phil Katzen. There was a small mound of quarters between the men and, instead of cards, both of them were using laptops linked by a cable. As she walked past them, Ann could tell Stoll was losing. He freely admitted that he had the worst poker face on the planet. Whenever things weren't going well, whether he was playing cards or trying to fix a computer responsible for the defense of the free world, sweat collected on every pore of his round, cherubic face.

Stoll surrendered a six of spades and a four of clubs. Phil dealt him a five of spades and a seven of hearts in return.

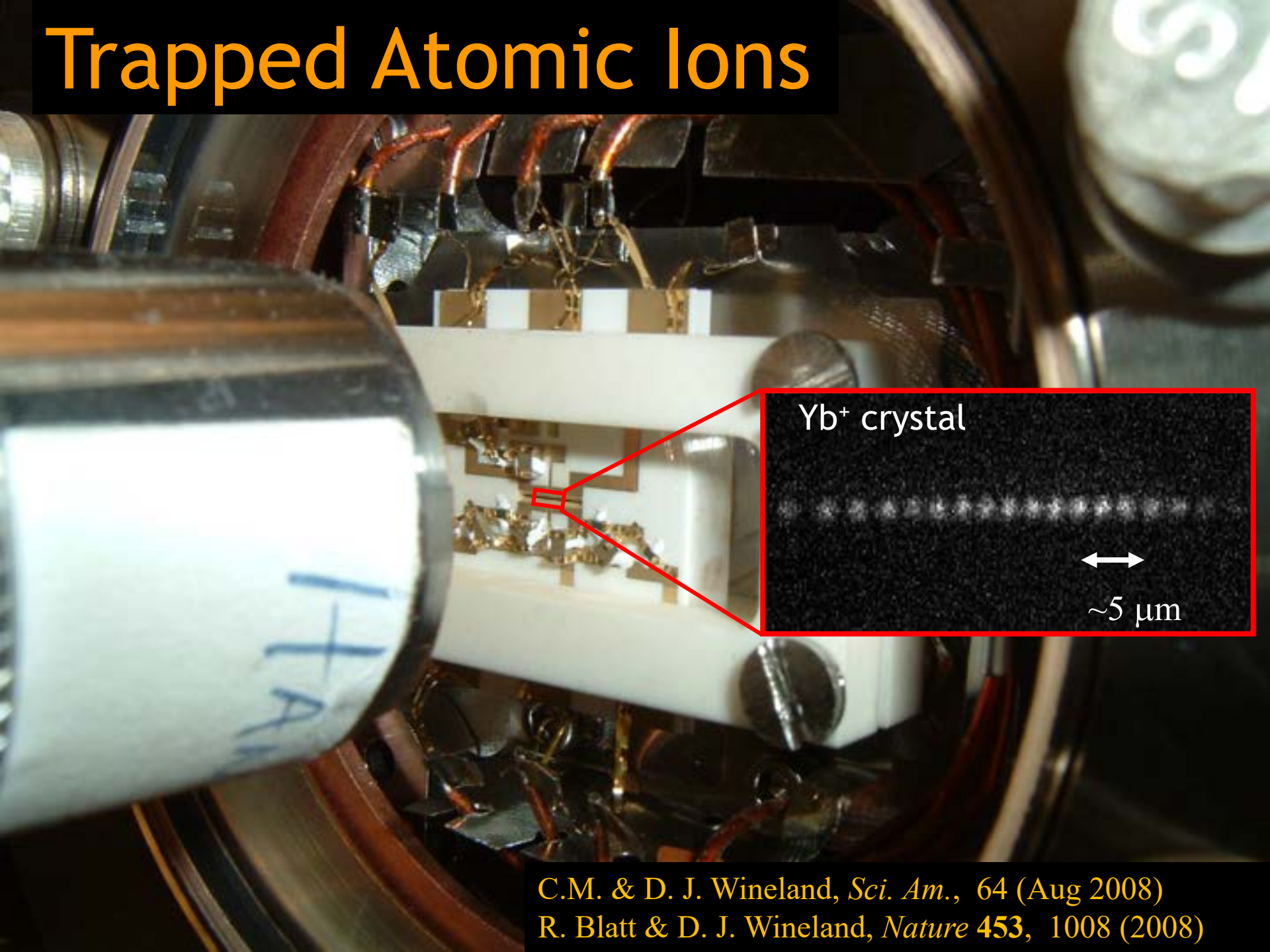
"Well, at least I've got a higher card now," Matt said, folding. "One more hand," he said. "Too bad this isn't like quantum computing. You confine ions in webs of magnetic and electric fields, hit a trapped particle with a burst of laser light to send it into an excited energy state, then hit it again to ground it. That's your switch. Rows of ions in a quantum logical gate, giving you the smallest, fastest computer on earth. Neat, clean, perfect."

"Yeah," Phil said, "too bad this isn't like that."

"Don't be sarcastic," Stoll said as he popped the last of a chocolate-covered doughnut in his mouth, then washed it down with black coffee. "Next time we'll play baccarat and things will be different."

"No they won't," Katzen said, sitting back as he

Trapped Atomic Ions

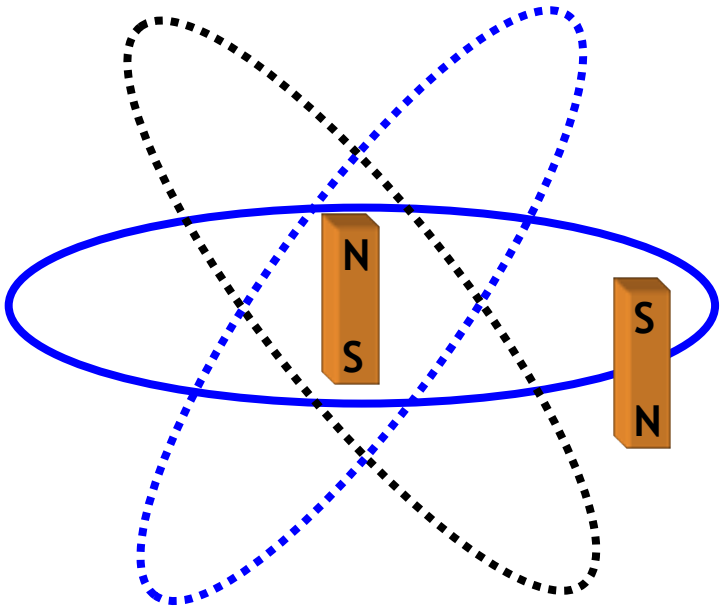


C.M. & D. J. Wineland, *Sci. Am.*, 64 (Aug 2008)
R. Blatt & D. J. Wineland, *Nature* **453**, 1008 (2008)

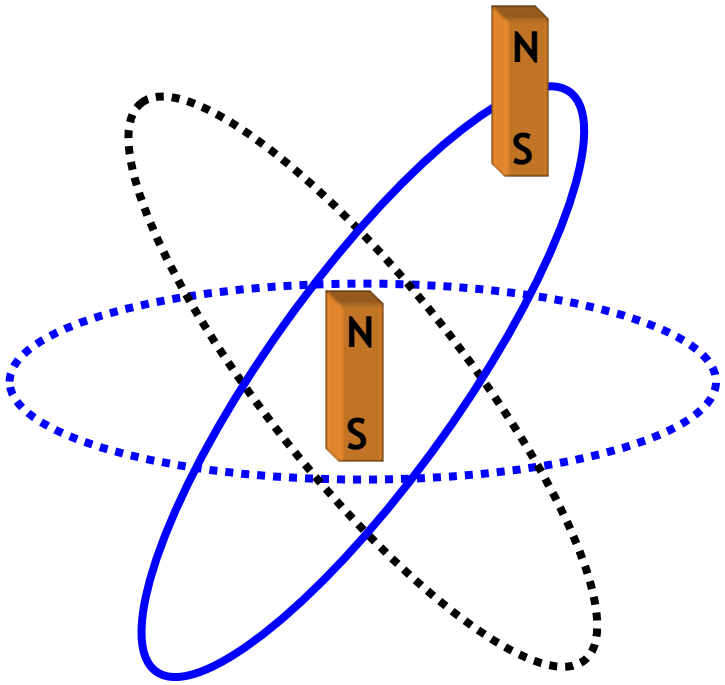
Quantum bit inside an atom:

States of relative electron/nuclear spin

State $|\downarrow\rangle$



State $|\uparrow\rangle$



PERIODIC TABLE

Atomic Properties of the Elements

Physics Laboratory NIST Standard Reference Data Program

physics.nist.gov www.nist.gov www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	$m_e c^2$	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Group: IA, IIA, IIIA, IVA, VA, VIA, VIIA, VIIIA, IB, IIB, IIIB, IVB, VB, VIB, VIIB, VIII

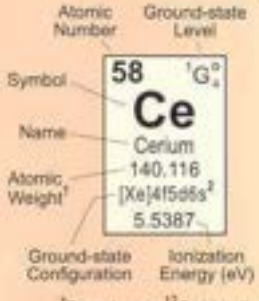
Period: 1–7

Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 $^2S_{1/2}$ **H** Hydrogen 1.00794 $1s$ 13.5984																	2 $^1S_0$ **He** Helium 4.002602 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.941 $1s^2 2s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.012182 $1s^2 2s^2$ 9.3227																
3	11 $^2S_{1/2}$ **Na** Sodium 22.98977 [Ne]$3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.3050 [Ne]$3s^2$ 7.6462																
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 [Ar]$4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 [Ar]$4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.95591 [Ar]$3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 [Ar]$3d^2 4s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]$3d^3 4s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 [Ar]$3d^5 4s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.93805 [Ar]$3d^5 4s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 [Ar]$3d^6 4s^2$ 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.93320 [Ar]$3d^7 4s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 [Ar]$3d^8 4s^2$ 7.6398	29 $^2S_{1/2}$ **Cu** Copper 63.546 [Ar]$3d^{10} 4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.39 [Ar]$3d^{10} 4s^2$ 9.3942	31 $^2P^o_{1/2}$ **Ga** Gallium 69.723 [Ar]$3d^{10} 4s^2 4p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.61 [Ar]$3d^{10} 4s^2 4p^2$ 7.8994	33 $^4S^o_{3/2}$ **As** Arsenic 74.92160 [Ar]$3d^{10} 4s^2 4p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.96 [Ar]$3d^{10} 4s^2 4p^4$ 9.7524	35 $^2P^o_{3/2}$ **Br** Bromine 79.904 [Ar]$3d^{10} 4s^2 4p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.80 [Ar]$3d^{10} 4s^2 4p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]$5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 [Kr]$5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90585 [Kr]$4d5s^2$ 6.2171	40 $^3F_2$ **Zr** Zirconium 91.224 [Kr]$4d^2 5s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 [Kr]$4d^4 5s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.94 [Kr]$4d^5 5s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) [Kr]$4d^5 5s^2$ 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 [Kr]$4d^7 5s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]$4d^8 5s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 [Kr]$4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]$4d^{10} 5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.411 [Kr]$4d^{10} 5s^2$ 8.9938	49 $^2P^o_{1/2}$ **In** Indium 114.818 [Kr]$4d^{10} 5s^2 5p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 [Kr]$4d^{10} 5s^2 5p^2$ 7.3439	51 $^4S^o_{3/2}$ **Sb** Antimony 121.760 [Kr]$4d^{10} 5s^2 5p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 [Kr]$4d^{10} 5s^2 5p^4$ 9.0096	53 $^2P^o_{3/2}$ **I** Iodine 126.90447 [Kr]$4d^{10} 5s^2 5p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.29 [Kr]$4d^{10} 5s^2 5p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.90545 [Xe]$6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.327 [Xe]$6s^2$ 5.2117	72 $^3F_2$ **Hf** Hafnium 178.49 [Xe]$4f^{14} 5d^2 6s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.9479 [Xe]$4f^{14} 5d^3 6s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 [Xe]$4f^{14} 5d^4 6s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]$4f^{14} 5d^5 6s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 [Xe]$4f^{14} 5d^6 6s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]$4f^{14} 5d^7 6s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.078 [Xe]$4f^{14} 5d^9 6s$ 8.9587	79 $^2S_{1/2}$ **Au** Gold 196.96655 [Xe]$4f^{14} 5d^{10} 6s$ 9.2255	80 $^1S_0$ **Hg** Mercury 200.59 [Xe]$4f^{14} 5d^{10} 6s^2$ 10.4375	81 $^2P^o_{1/2}$ **Tl** Thallium 204.3833 [Hg]$6p$ 6.1082	82 $^3P_0$ **Pb** Lead 207.2 [Hg]$6p^2$ 7.4167	83 $^4S^o_{3/2}$ **Bi** Bismuth 208.98038 [Hg]$6p^3$ 7.2856	84 $^3P_2$ **Po** Polonium (209) [Hg]$6p^4$ 8.417 ?	85 $^2P^o_{3/2}$ **At** Astatine (210) [Hg]$6p^5$	86 $^1S_0$ **Rn** Radon (222) [Hg]$6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) [Rn]$7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) [Rn]$7s^2$ 5.2784	104 $^3F_2$? **Rf** Rutherfordium (261) [Rn]$5f^{14} 6d^2 7s^2$? 6.0 ?	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (268)	110 **Uun** Ununnilium (269)	111 **Uuu** Ununnium (272)	112 **Uub** Ununbium								

Lanthanoids														
57 $^2D_{3/2}$ **La** Lanthanum 138.9055 [Xe]$5d6s^2$ 5.5769	58 $^1G^o_4$ **Ce** Cerium 140.116 [Xe]$4f5d6s^2$ 5.5387	59 $^4I^o_{9/2}$ **Pr** Praseodymium 140.90765 [Xe]$4f^3 6s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.24 [Xe]$4f^4 6s^2$ 5.5250	61 $^6H^o_{5/2}$ **Pm** Promethium (145) [Xe]$4f^5 6s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 [Xe]$4f^6 6s^2$ 5.6436	63 $^8S^o_{7/2}$ **Eu** Europium 151.964 [Xe]$4f^7 6s^2$ 5.6704	64 $^9D^o_2$ **Gd** Gadolinium 157.25 [Xe]$4f^7 5d6s^2$ 6.1501	65 $^6H^o_{15/2}$ **Tb** Terbium 158.92534 [Xe]$4f^9 6s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.50 [Xe]$4f^{10} 6s^2$ 5.9389	67 $^4I^o_{15/2}$ **Ho** Holmium 164.93032 [Xe]$4f^{11} 6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.26 [Xe]$4f^{12} 6s^2$ 6.1077	69 $^2F^o_{7/2}$ **Tm** Thulium 168.93421 [Xe]$4f^{13} 6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.04 [Xe]$4f^{14} 6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.967 [Xe]$4f^{14} 5d6s^2$ 5.4259
Actinoids														
89 $^2D_{3/2}$ **Ac** Actinium (227) [Rn]$6d7s^2$ 5.17	90 $^3F_2$ **Th** Thorium 232.0381 [Rn]$6d^2 7s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]$5f^2 6d7s^2$ 5.89	92 $^5L_6$ **U** Uranium 238.0289 [Rn]$5f^3 6d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) [Rn]$5f^4 6d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) [Rn]$5f^6 7s^2$ 6.0262	95 $^8S^o_{7/2}$ **Am** Americium (243) [Rn]$5f^7 7s^2$ 5.9738	96 $^9D^o_2$ **Cm** Curium (247) [Rn]$5f^7 6d7s^2$ 5.9915	97 $^6H^o_{15/2}$ **Bk** Berkelium (247) [Rn]$5f^9 7s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) [Rn]$5f^{10} 7s^2$ 6.2817	99 $^4I^o_{15/2}$ **Es** Einsteinium (252) [Rn]$5f^{11} 7s^2$ 6.42	100 $^3H_6$ **Fm** Fermium (257) [Rn]$5f^{12} 7s^2$ 6.50	101 $^2F^o_{7/2}$ **Md** Mendelevium (258) [Rn]$5f^{13} 7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) [Rn]$5f^{14} 7s^2$ 6.65	103 $^2P^o_{1/2}$? **Lr** Lawrencium (262) [Rn]$5f^{14} 7s^2 7p$? 4.9 ?

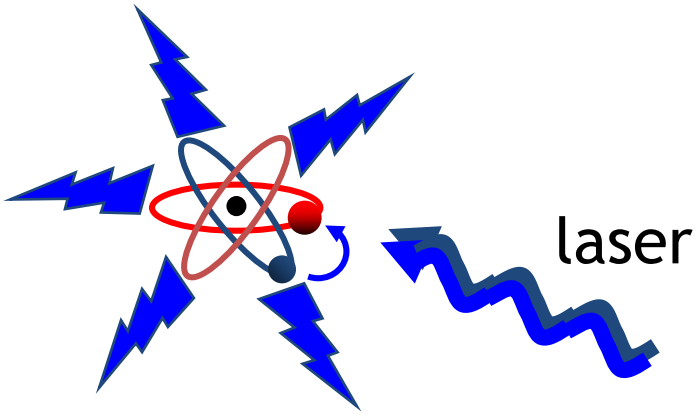
Solids
Liquids
Gases
Artificially Prepared

For a description of the atomic data, visit physics.nist.gov/atomic



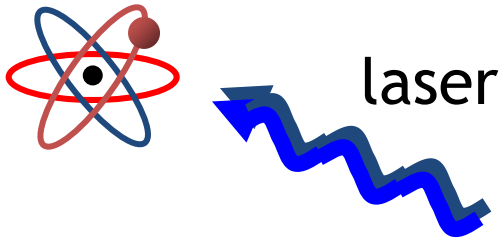
“Perfect” quantum measurement of a single atom

state $|\downarrow\rangle$

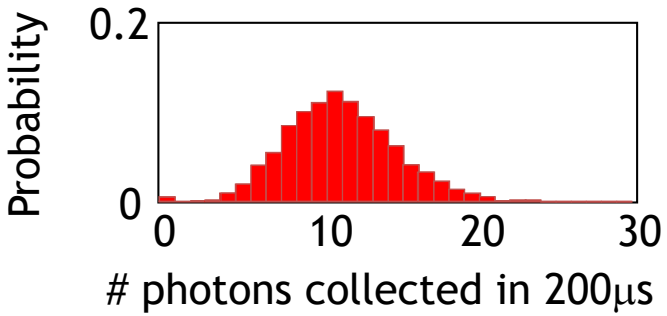


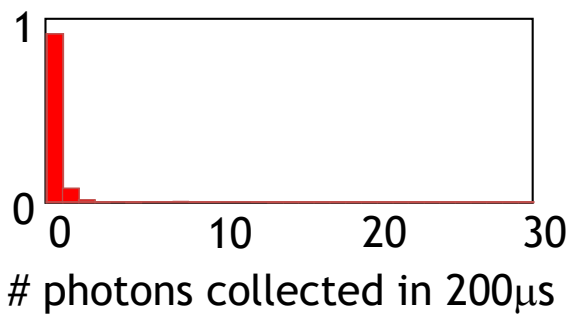
atom fluoresces 10^8 photons/sec

state $|\uparrow\rangle$



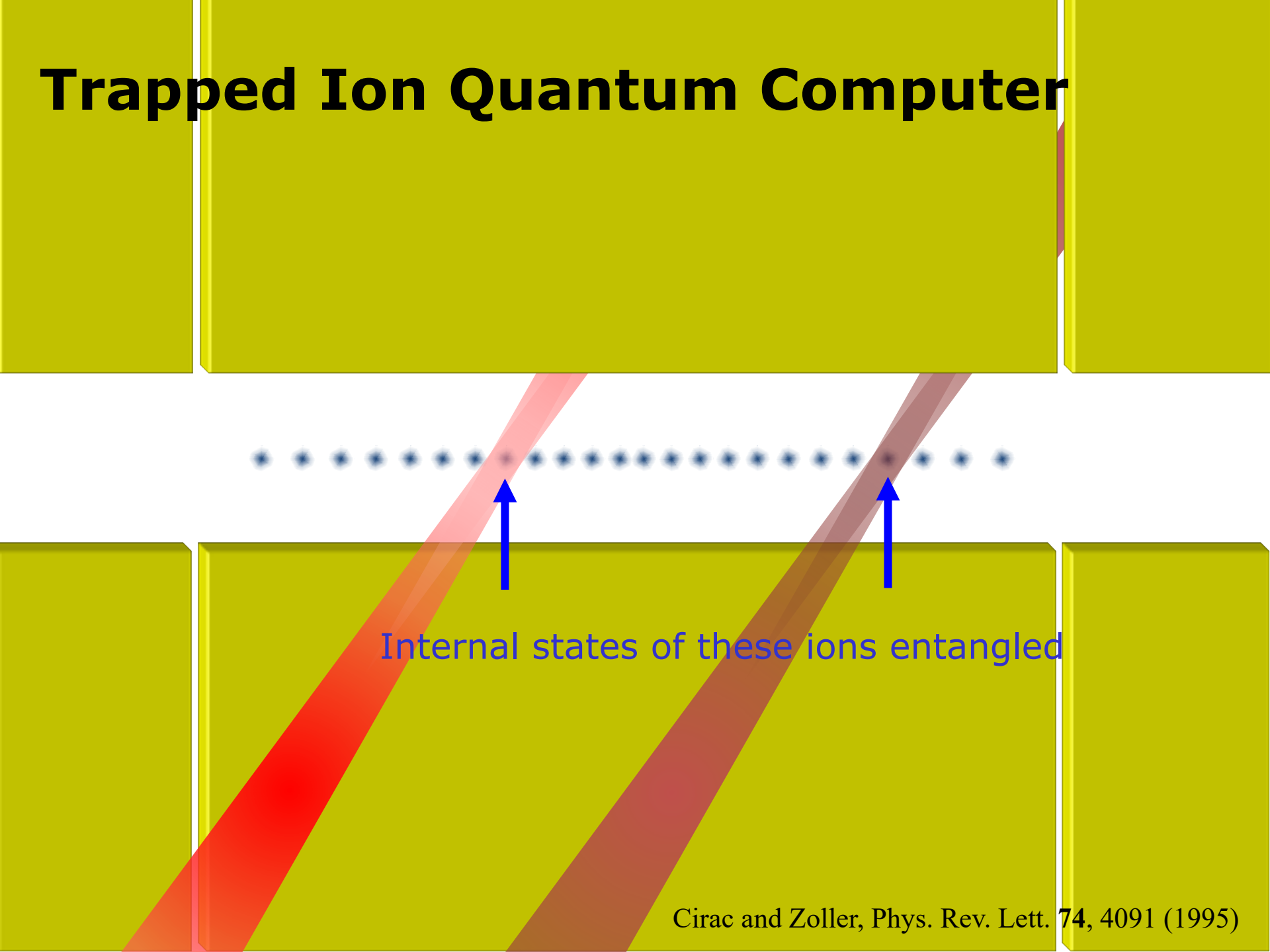
atom remains dark





>99% detection efficiency!

Trapped Ion Quantum Computer

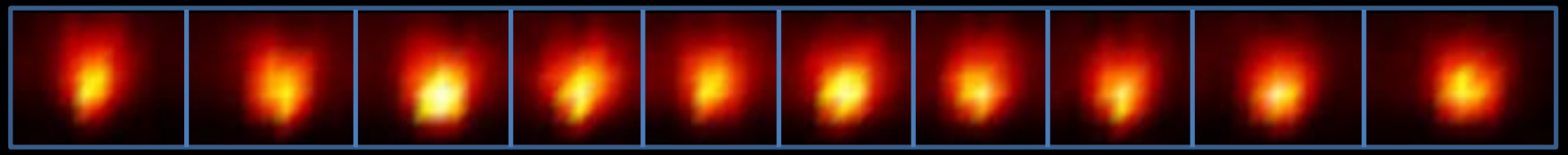


Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

Antiferromagnetic Néel order of N=10 spins

2600 runs, α=1.12

All in state ↑

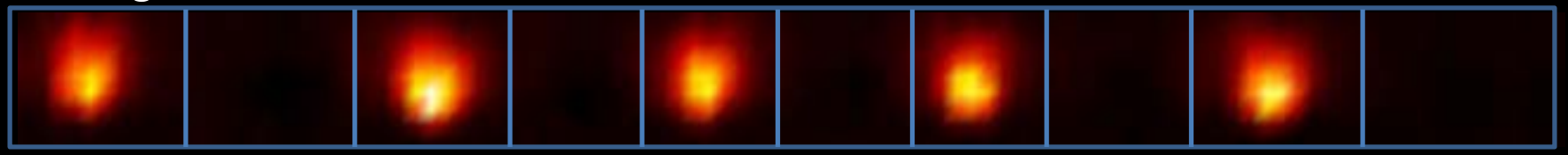


All in state ↓

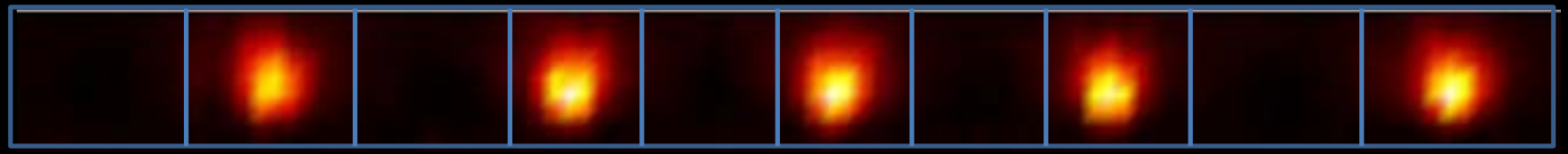


AFM ground state order

222 events



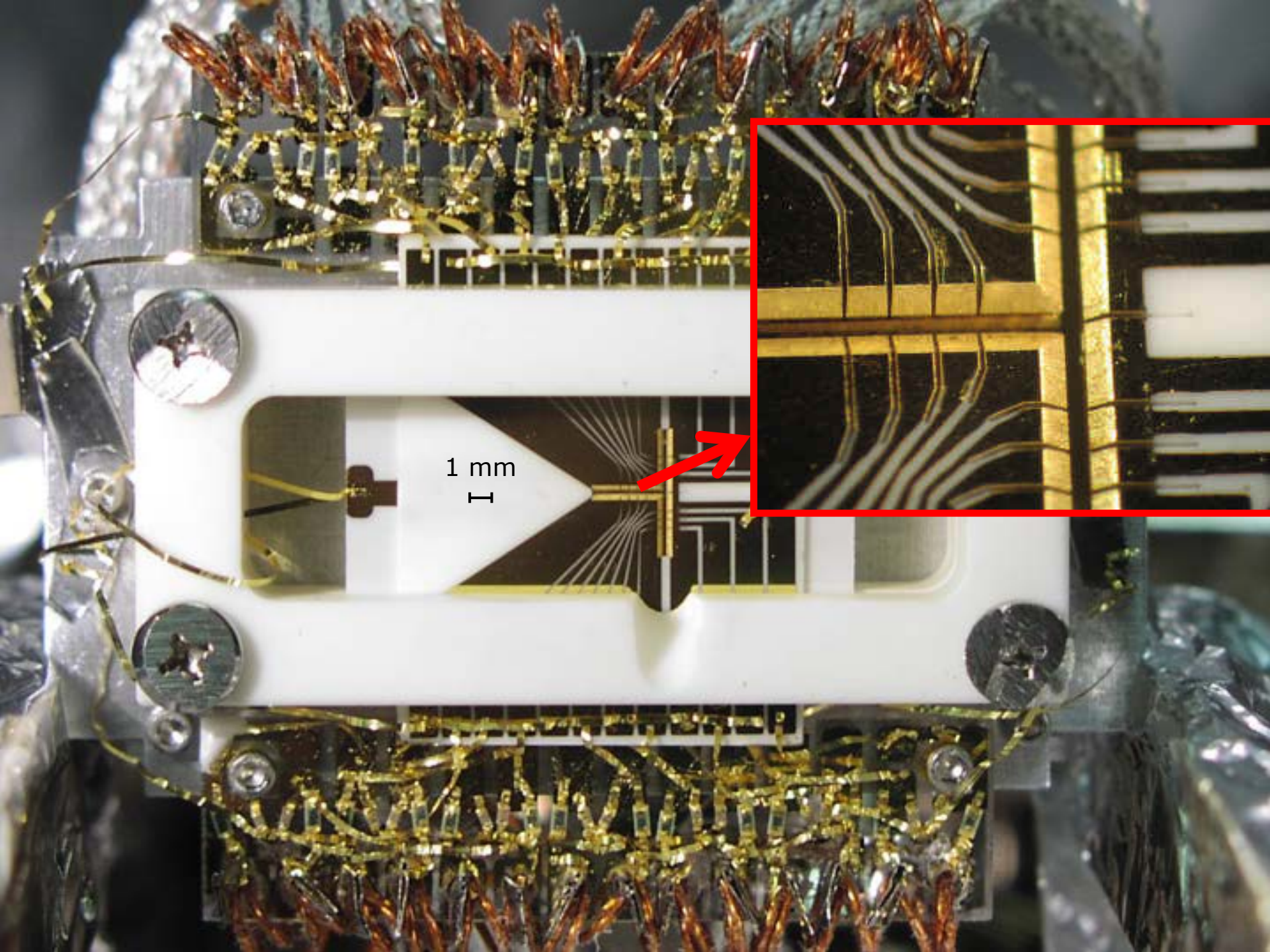
219 events

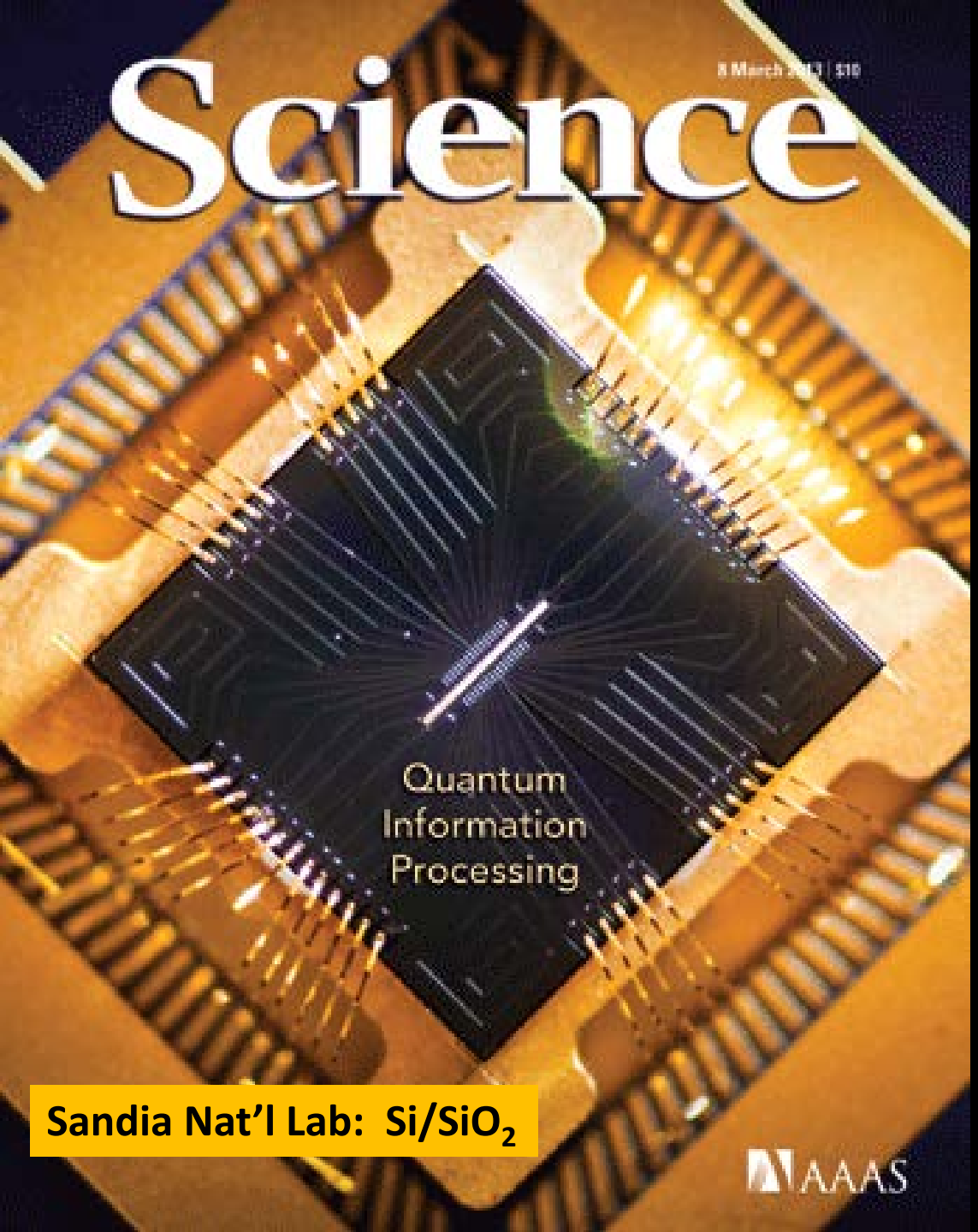


441 events out of 2600 = 17**%**

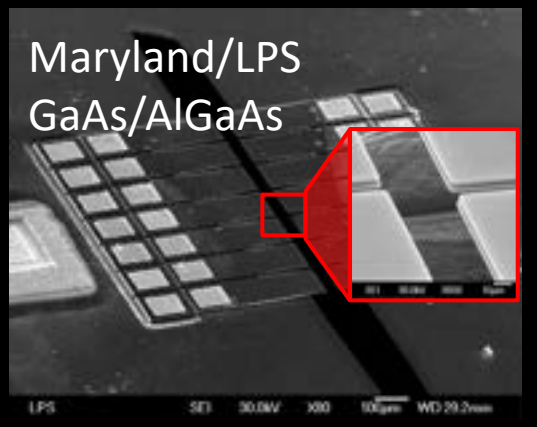
Prob of any state at random =2 x $(1/2^{10})$ = 0.2%

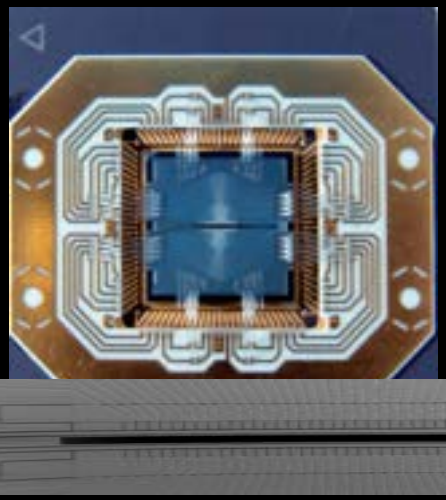

(see K. Brown)
cooling beam


1 mm

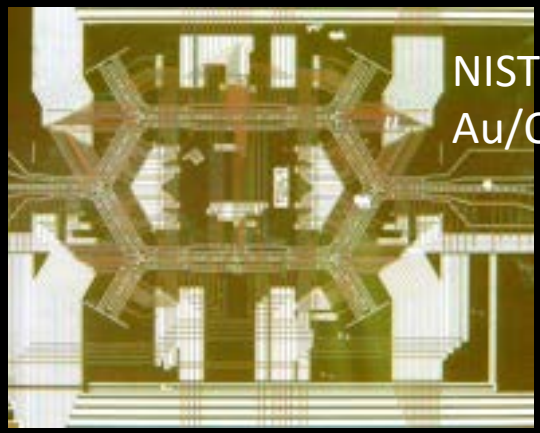


Sandia Nat'l Lab: Si/SiO_2





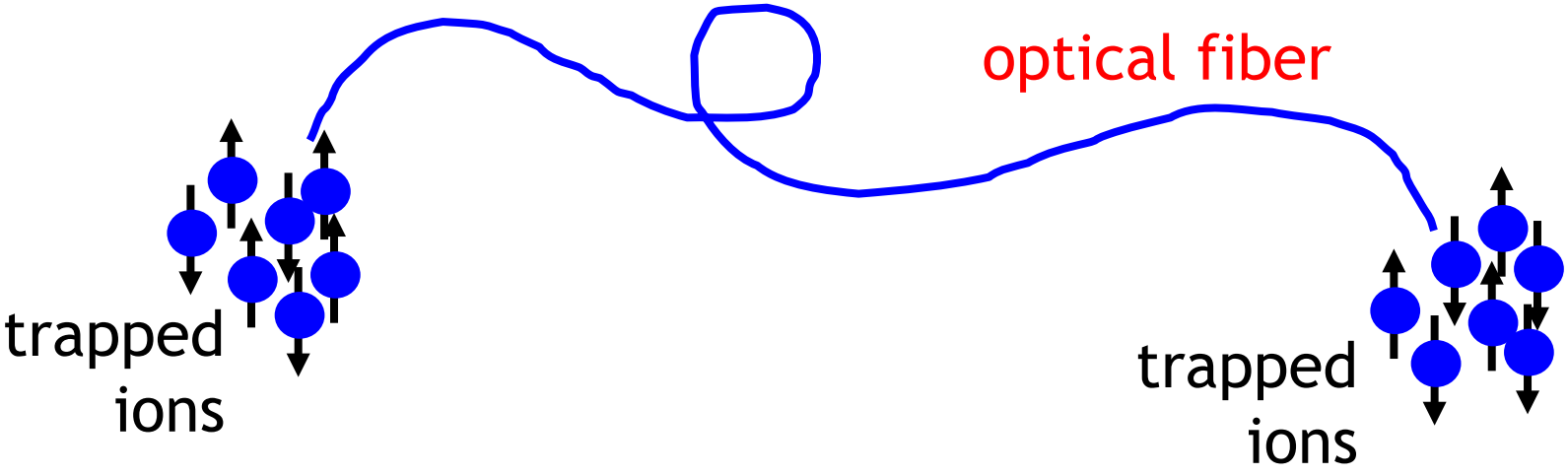
GaTech
Res. Inst.
Al/Si/SiO_2

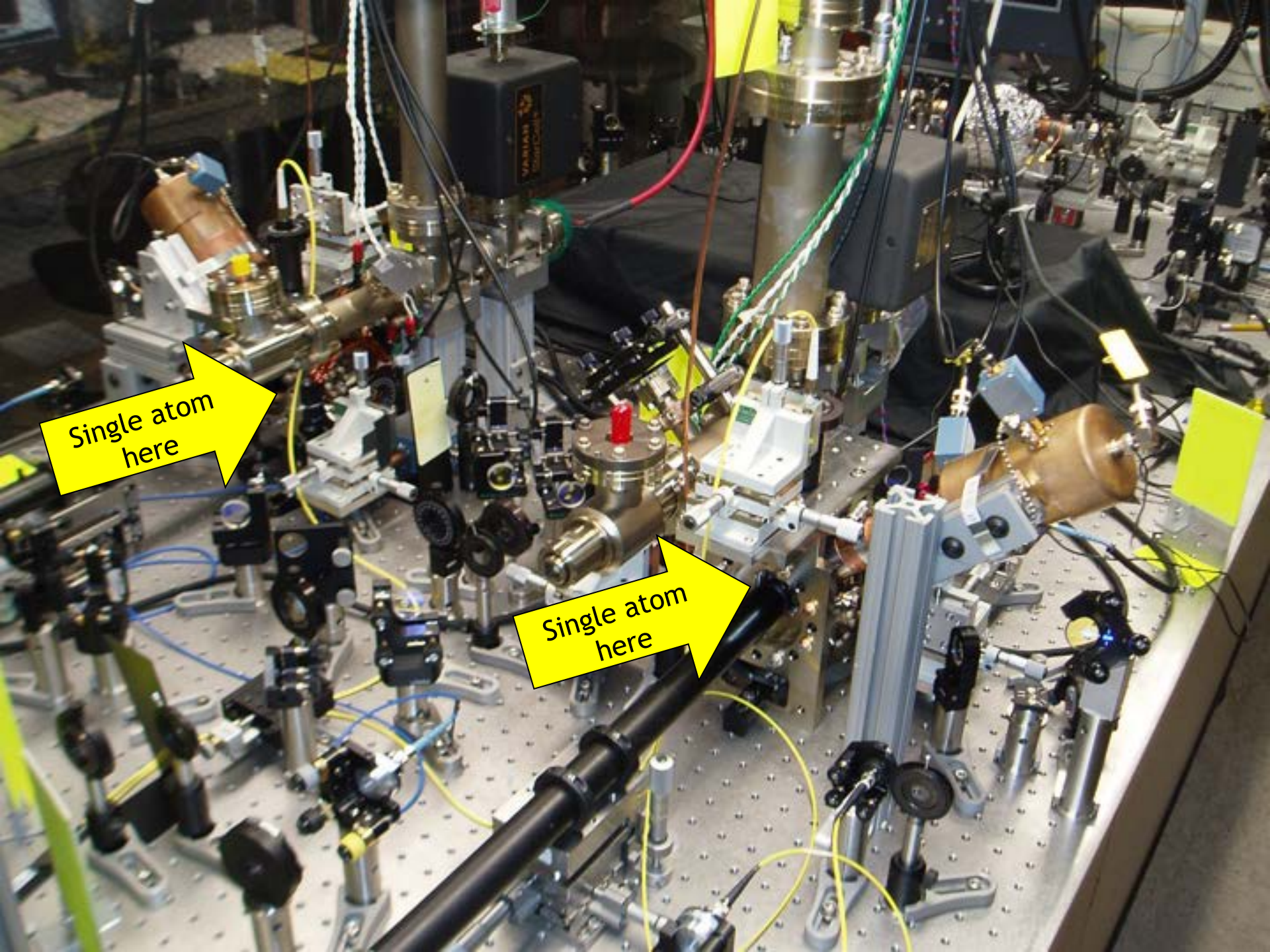


NIST-Boulder
Au/Quartz

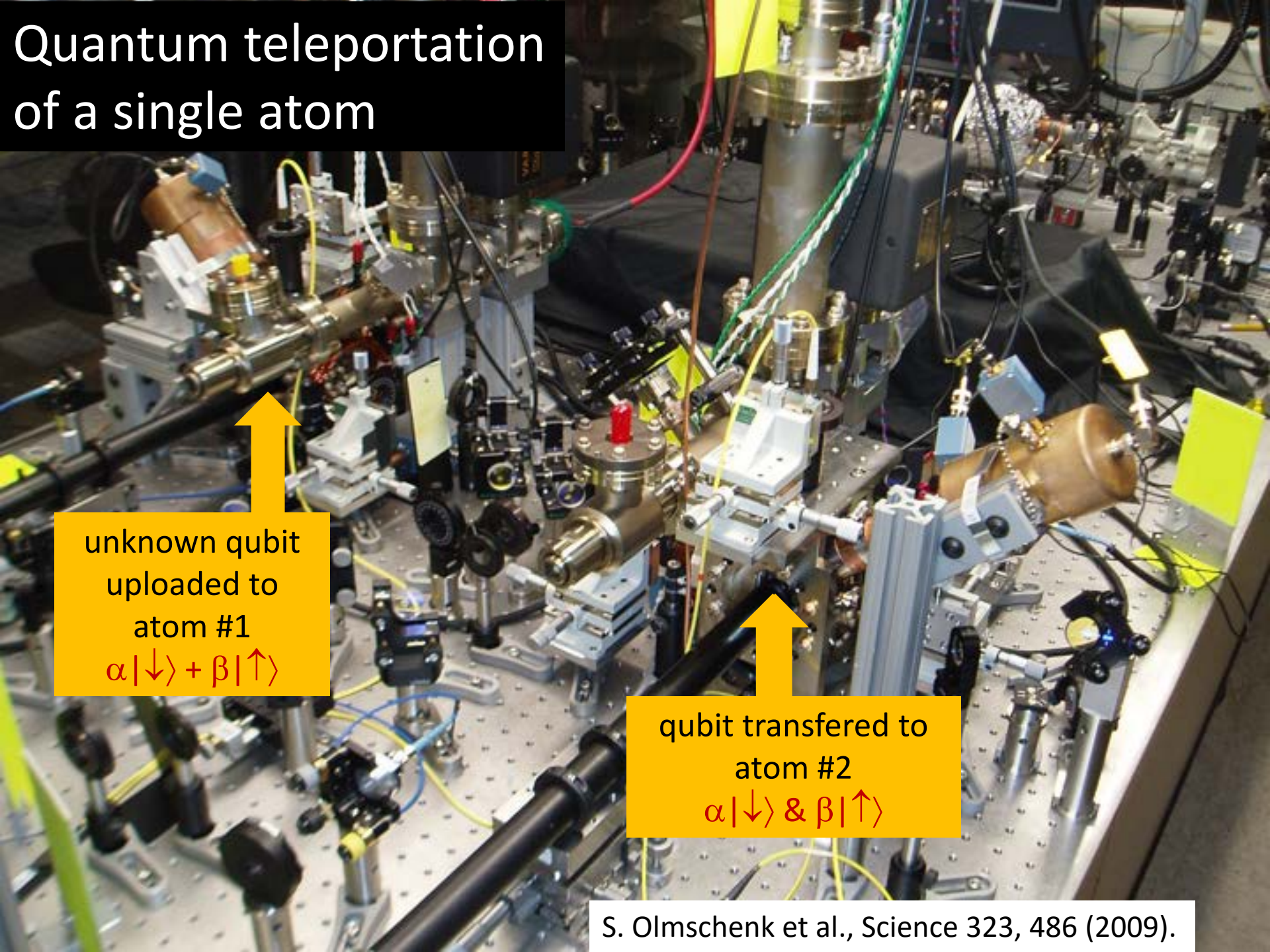
Photonic Quantum Networking

Linking ideal quantum memory (trapped ion) with ideal quantum communication channel (photon)




Single atom here
Single atom here

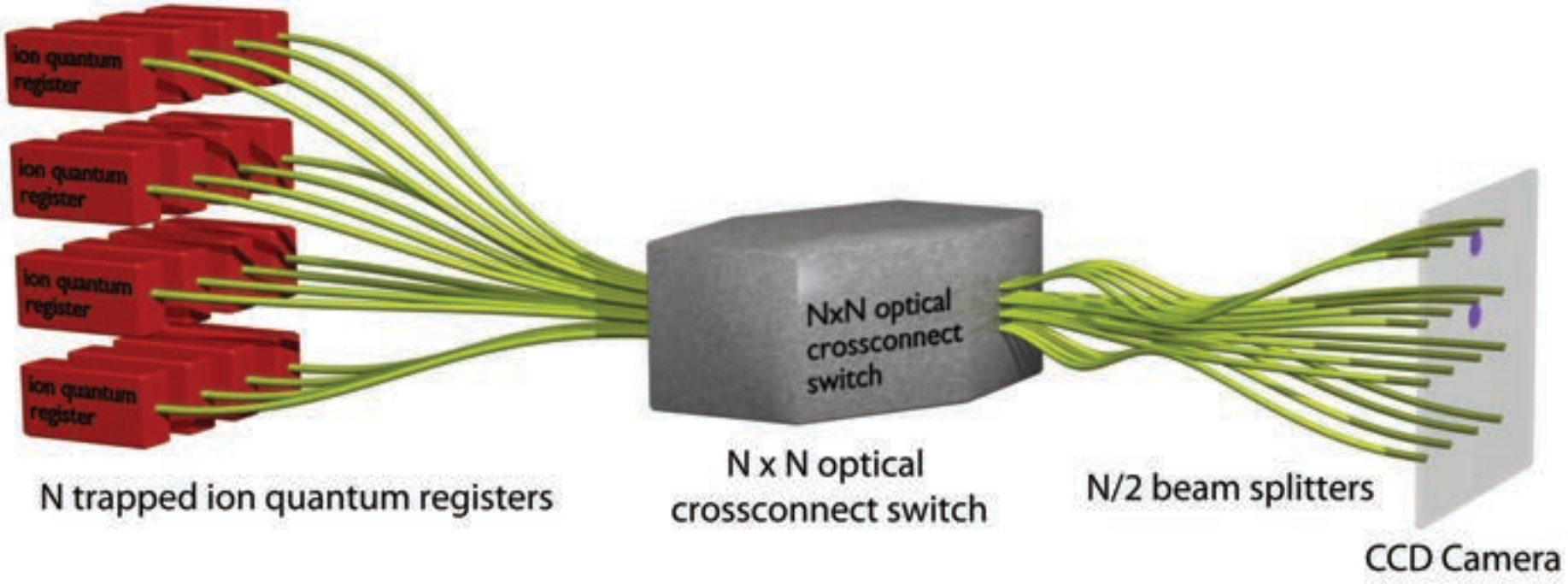
Quantum teleportation of a single atom



S. Olmschenk et al., Science 323, 486 (2009).

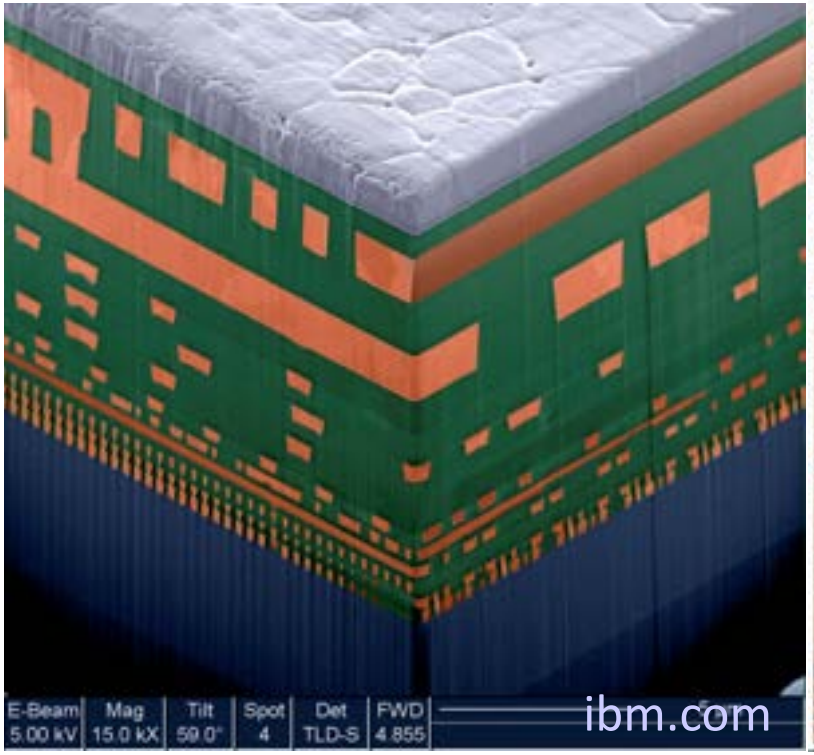

we need
more time..
and more
qubits..

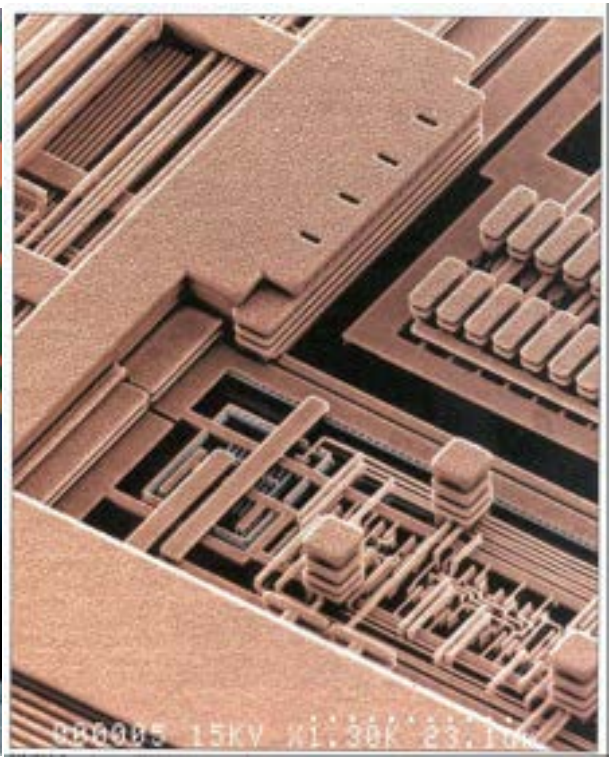
Large scale vision (10^3 – 10^6 atomic qubits)

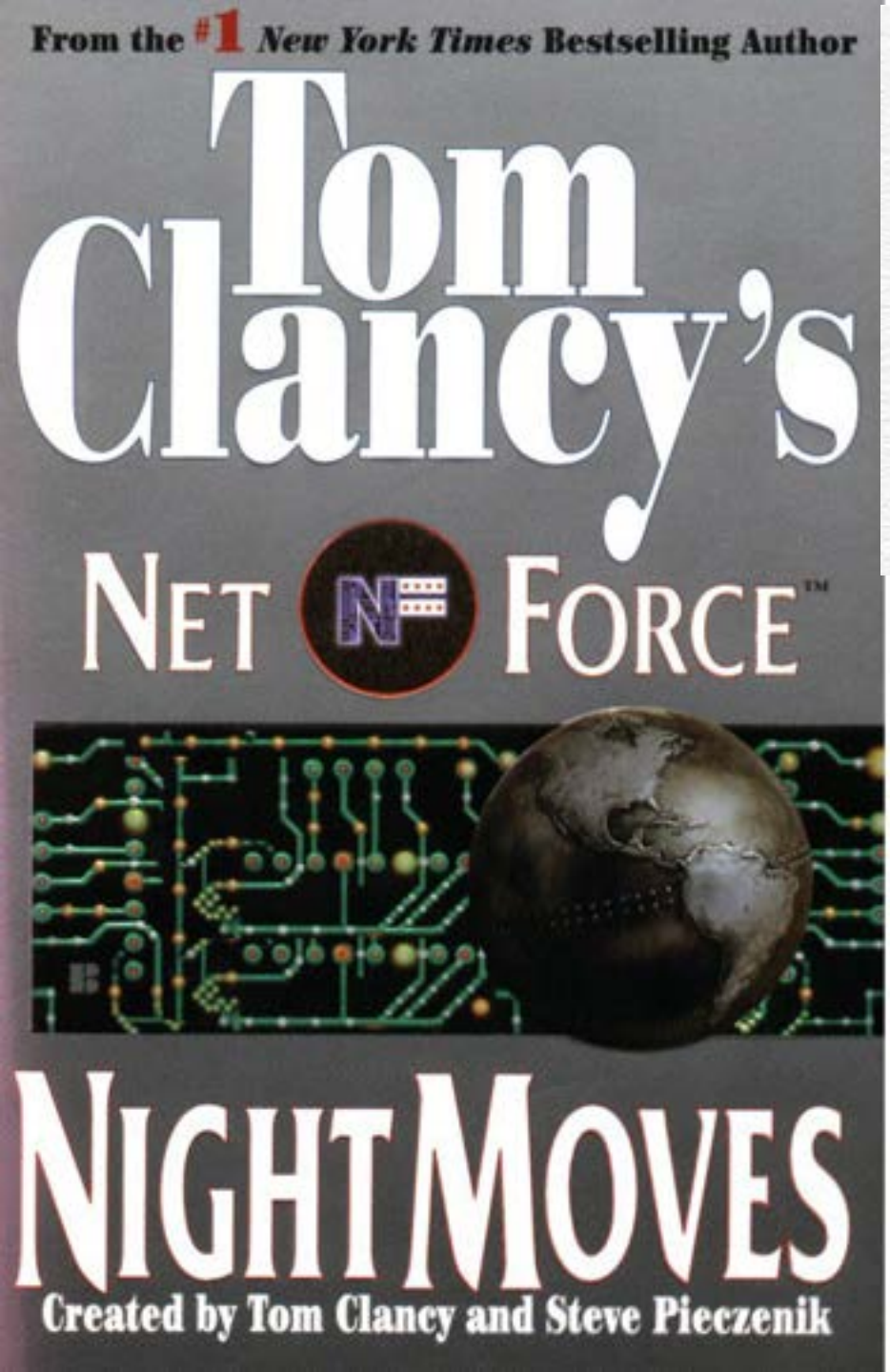


Classical Computer Architecture

- 1 layer of transistors, 9-12 layers of connectors
- Interconnect complexity determines circuit complexity
- Efficient transport of bits in the computer is crucial







Bascomb-Coombs went on: "Using Shor's quantum factorization algorithm, one can see that factoring a large number can be done by a QC—quantum computer—in a very small fraction of the time the same number would take using ordinary hardware. A problem that a SuperCray might labor over for a few million years can be done in seconds by my QC. So for a practical matter like code breaking, the QC is vastly superior."

Peel nodded. "If so, why isn't everybody using these QCs?"

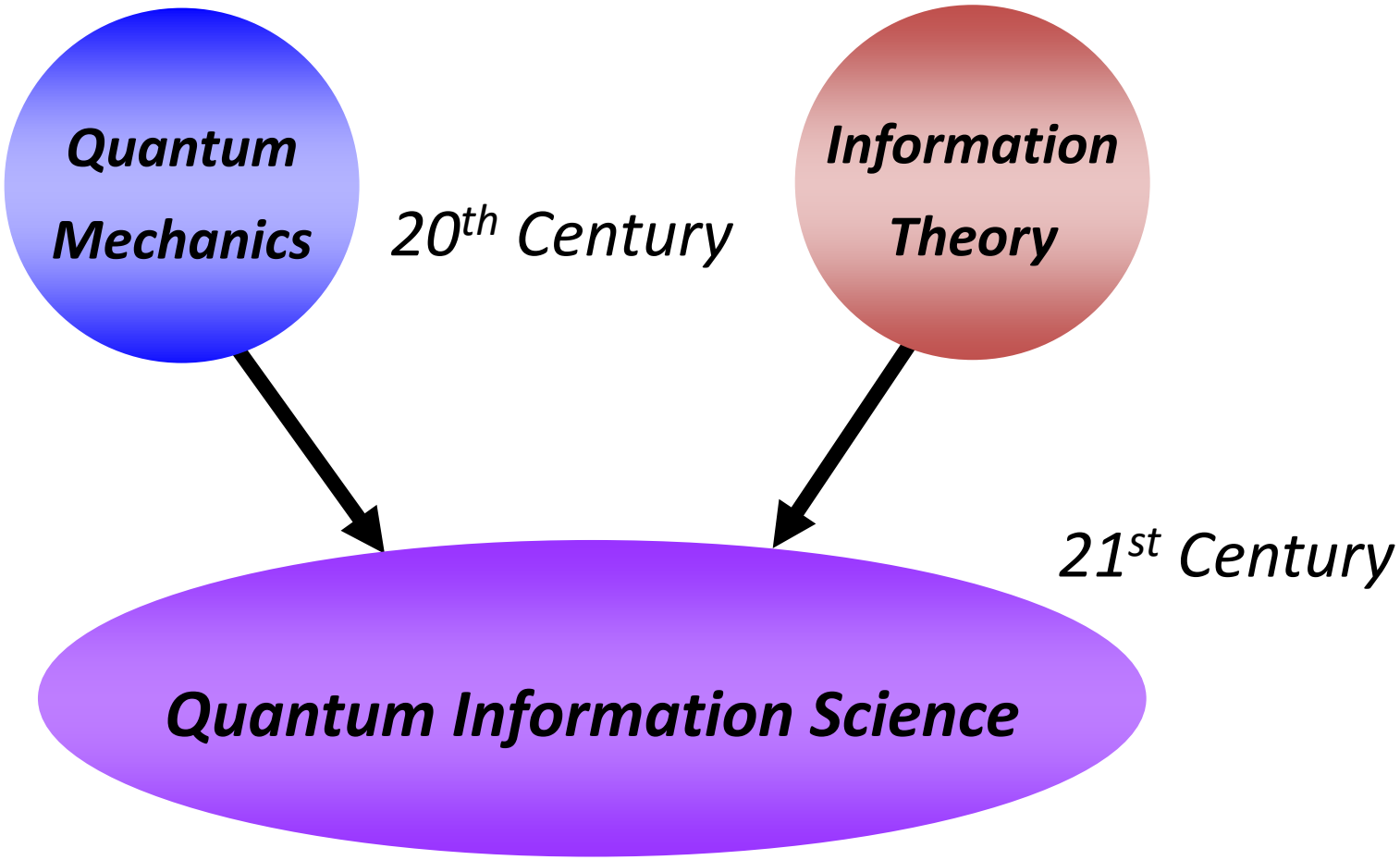
Bascomb-Coombs laughed again. "Oh, they would much like to! But it isn't something one whips up in an old mayonnaise jar out in the woodshed. The problem is that the coherent state of a QC is usually destroyed as soon as it is affected by the surrounding environment. What this means is, as soon as you turn it on and try to access it, you destroy it. A bit of a trick to get around that. They've tried all kinds of things over the years: lasers, photon excitation, ion traps, optical traps, NMR, polarization, and even Bulk Spin-Resonance—quantum tea leaves, this last.

"Wineland and Monroe worked out the single quantum gate by trapping beryllium ions. Kimble and Turch polarized photons and did the same thing. NTC had some early success with nuclear magnetic resonance, and Chuang and Gershenfeld applied Grover's algorithm for a 2Q model, using the carbon and hydrogen atoms in a chloroform molecule. But the problem has always been multiplicity and stability. Until my unit."

"How did you manage that, if it is so hard?"

"Because I am smarter than they are," he said. It didn't sound like bragging and, given the results, apparently it wasn't.

A new science for the 21st Century?



Physics
Chemistry
Computer Science

Electrical Engineering
Mathematics
Information Theory

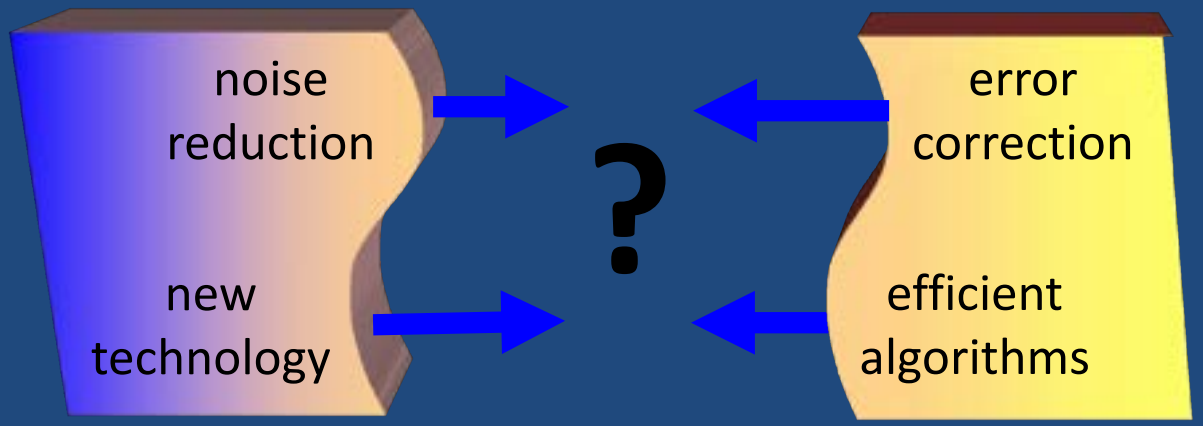
Quantum Computing Abyss

state-of-the-art experiments

theoretical requirements for "useful" QC

~ 20 # quantum bits **>1000**

<100 # logic gates **>10^9**




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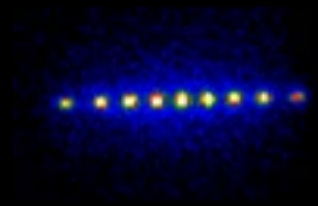
Quantum Information Hardware at

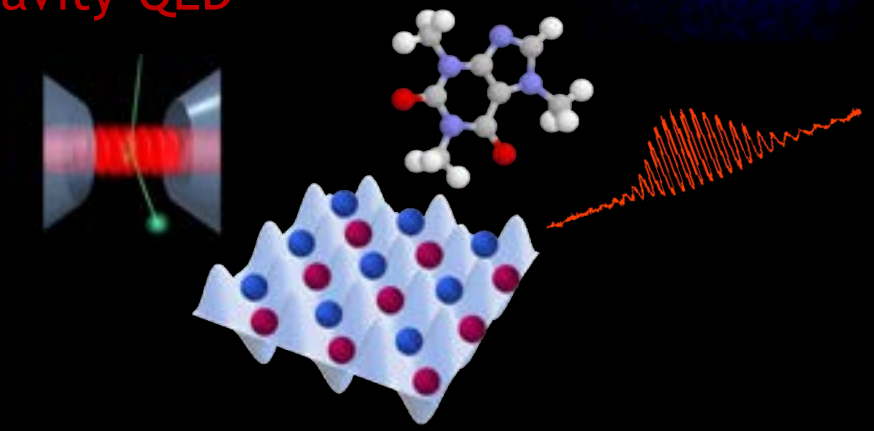
Individual atoms and photons

ion traps

atoms in optical lattices

cavity-QED

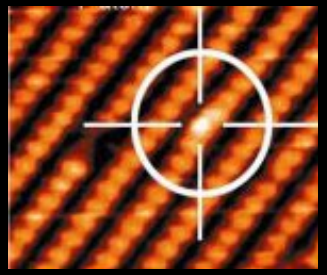


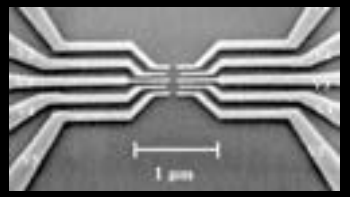


Semiconductors

quantum dots

2D electron gases

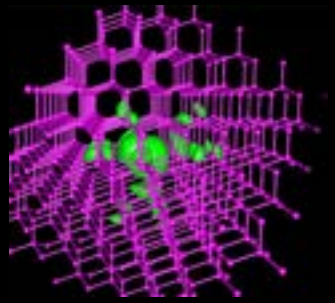


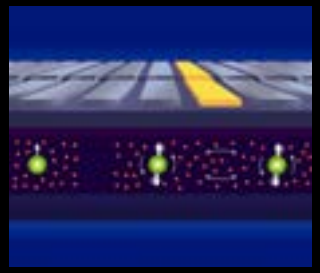


Other condensed-matter

single atomic impurities in glass

single phosphorus atoms in silicon

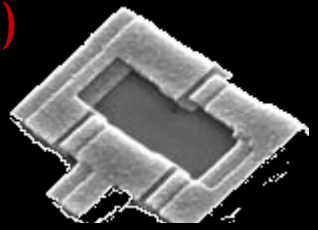




Superconductors

Cooper-pair boxes (charge qubits)

rf-SQUIDS (flux qubits)





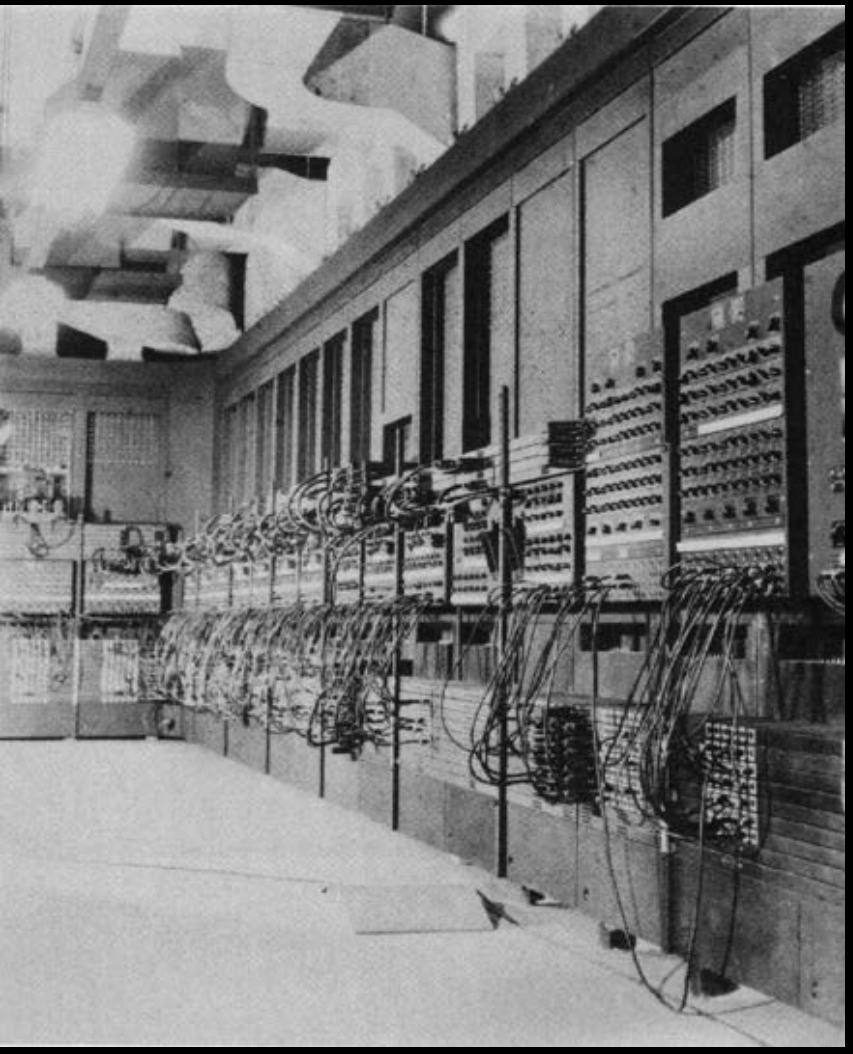
Yes, you can have one.

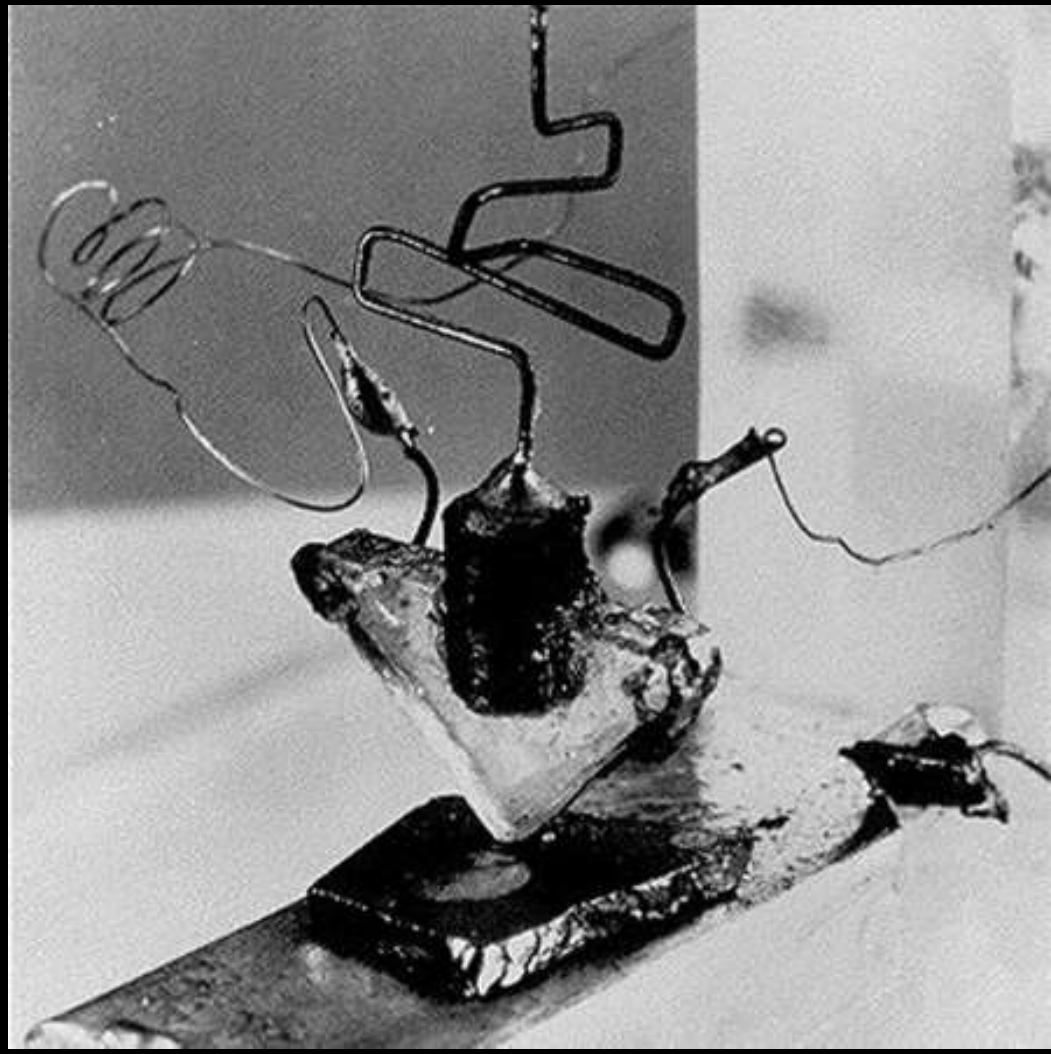
No, you're not dreaming. D-Wave offer the first commercial quantum computing system on the market. We believe in building great things that are as inspiring as they are powerful.

If you're passionate and curious about the future of computation, and you'd like to take a different approach to solving problems, then take a look at our products.

D-Wave One™ information

1947





Number cruncher turns 50

1st electronic computer feted

By Michael Raphael
The Associated Press

PHILADELPHIA — It had no monitor, could remember only 20 numbers at a time, and filled a room with 50 tons of electricity-sucking gear.

But it could crunch numbers with what seemed like blinding speed.

Fifty years ago this week, the Electronic Numerical Integrator and Computer was demonstrated for the first time at the University of Pennsylvania.

ENIAC counted to 5,000 in one-fifth of a second, shocking the world out of the mechanical age and into the world of lightning-quick digital processing.

ENIAC's collection of 8-foot-high gray cabinets made up the first general-purpose, large-scale, electronic computer.

Until then, "computers" were people using mechanical calculators who needed 12 hours to do what ENIAC did in half a minute. Other electronic machines had been narrower in purpose.

Granddaddy of computers turning 50

COMPUTERS from Page 1A

"Without it, we wouldn't have the space program, we wouldn't have modern airplanes," said Michael Williams, editor in chief of the Annals of the History of Computing. "Pilots would still be trying to fly by looking outside the window occasionally."

ENIAC long ago outgrew its usefulness as a number cruncher — a $40 calculator has more computing power.

But it has not lost its relevance.

The university planned an entire year of events to honor ENIAC's birthday, including turning on part of the original machine. Vice President Al Gore will throw a switch Wednesday, the day of the anniversary, and ENIAC will count from 46 to 96.

The Postal Service will unveil a stamp commemorating "The Birth of Computing." And Garry Kasparov, the World Chess Federation champion, this week is playing against IBM's "Deep Blue" computer.

The original assemblage of wires, vacuum tubes, resistors and switches was constructed in about a year and a half at the university's Moore School of Electrical Engineering.

When fully operational, ENIAC filled up a 30-by-50-foot room. Every second it was on, it used enough electricity — 174 kilowatts — to power a typical Philadelphia home for 1½ weeks.

Costing more than $486,000, ENIAC might never been attempted were it not for World War II.

"A lot of people said we were dreaming," said Herman Goldstine, who served as liaison between the Army and ENIAC team.

"The electronics people said there were too many vacuum tubes and it would never run. The mathematics people said there were no problems complex enough that computers were needed."

The Army provided both the complex problems and the money.

John Mauchly, one of two masterminds behind ENIAC, knew the Army was having a terrible time working out the complicated firing tables to help gun crews aim new artillery being used against German forces.

Each firing table had to list numbers for hundreds of potential trajectories. Calculating a single trajectory could take 40 hours using a mechanical desktop calculator, and 30 minutes using a sophisticated machine called a differential analyzer.

Mauchly, then 32, bravely told Army officials his machine could do the job in a matter of minutes.

ENIAC was completed just as the war was ending, too late for those artillery tables.

However, it fulfilled another military purpose. During test runs in 194 it did millions of calculations on the nuclear chain reactions, predicting the destruction that could be caused by the hydrogen bomb.



Associated Press

CALCULATING MINDS: J. Presper Eckert, left foreground, and John Mauchly, near pole, masterminded ENIAC, pictured in undated photo from the University of Pennsylvania Archives.

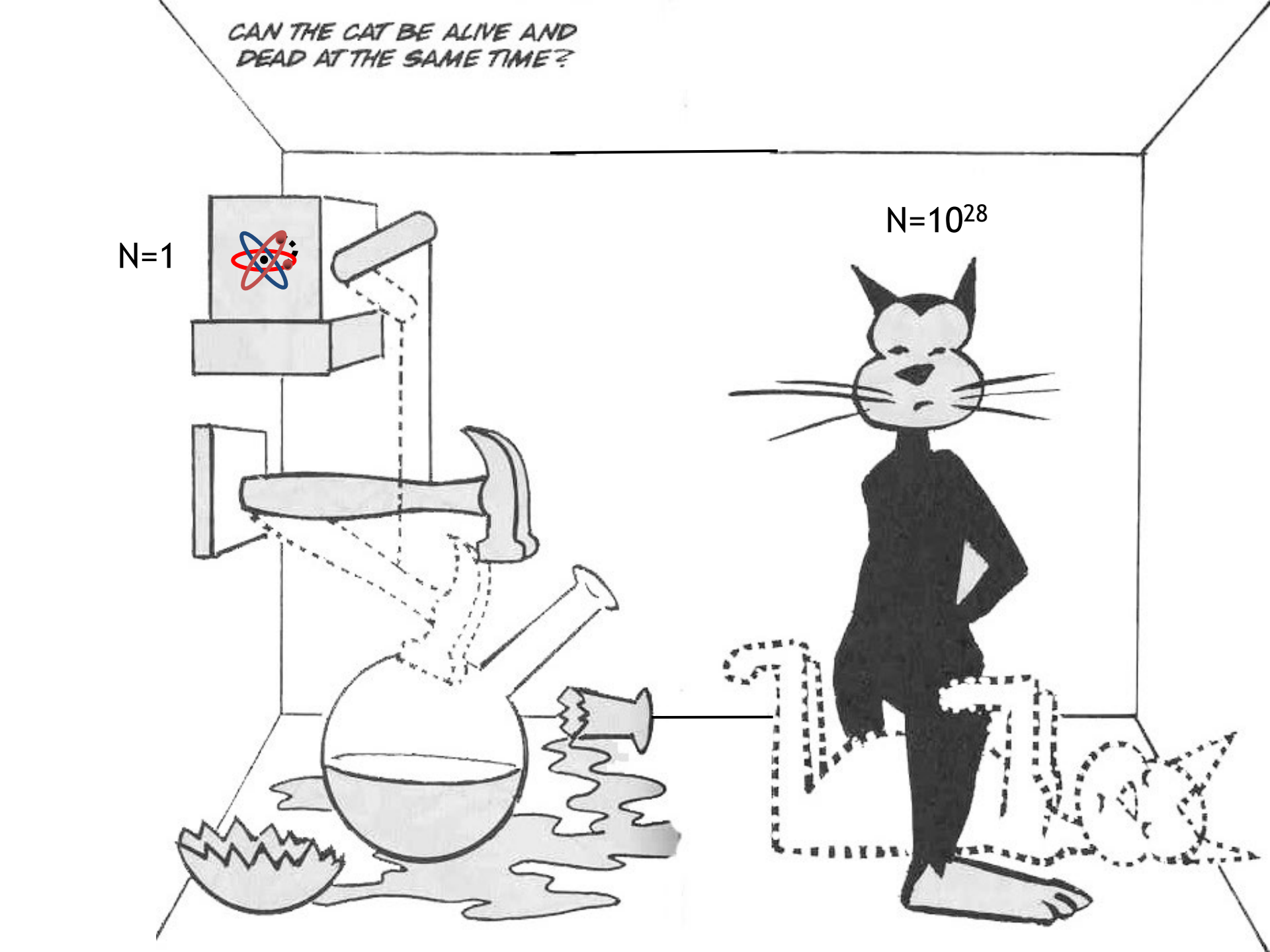
Richard Feynman (1982)



We have always had a great deal of difficulty in understanding the world view that quantum mechanics represents…

…Okay, I still get nervous with it…

It has not yet become obvious to me that there is no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.


CAN THE CAT BE ALIVE AND DEAD AT THE SAME TIME?
N=1
N=10^28

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Jonathan Mizrahi
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Jake Smith
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Undergrads

Daniel Brennan
Geoffrey Ji
Katie Hergenreder



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Taeyoung Choi
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