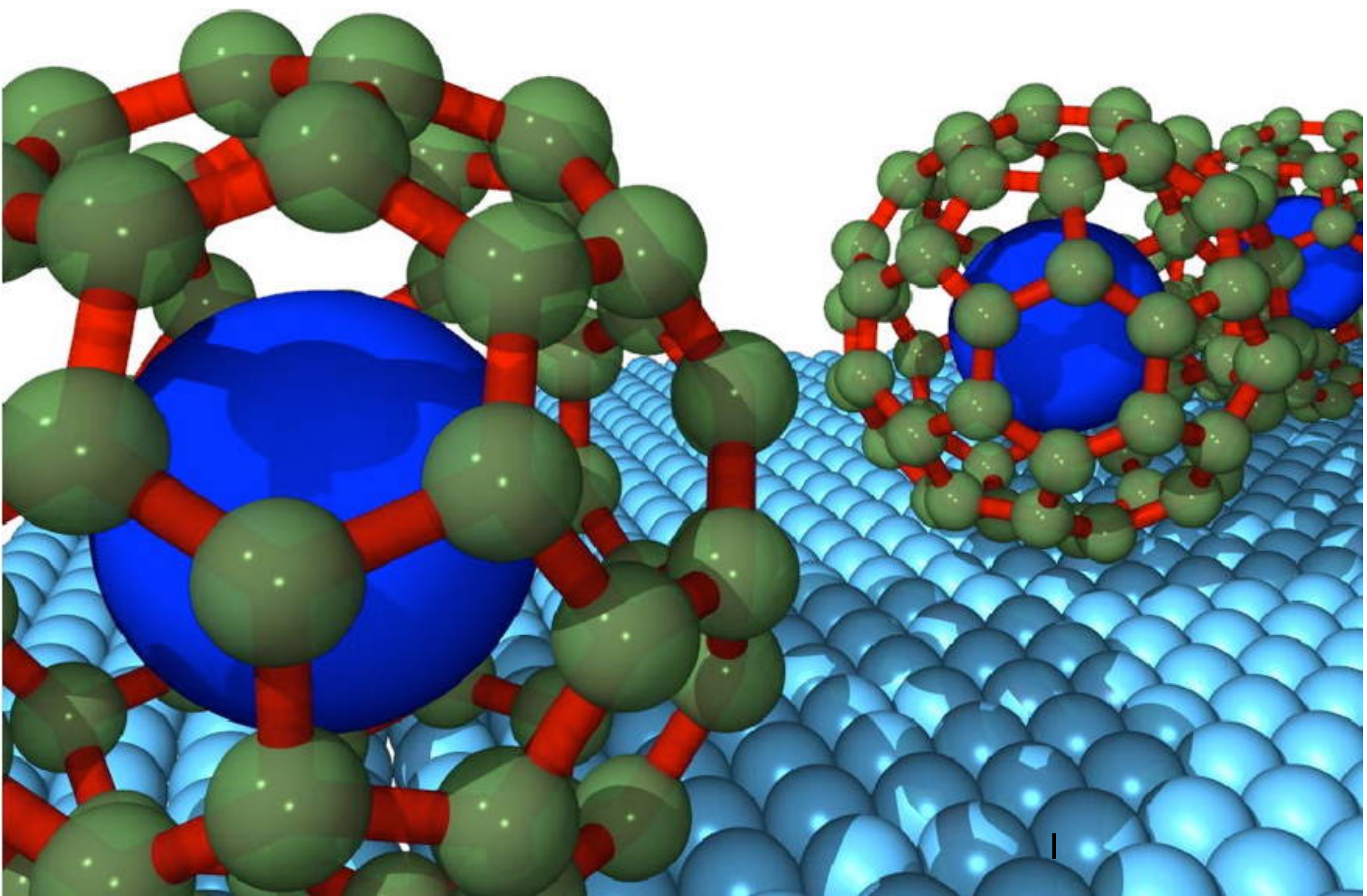
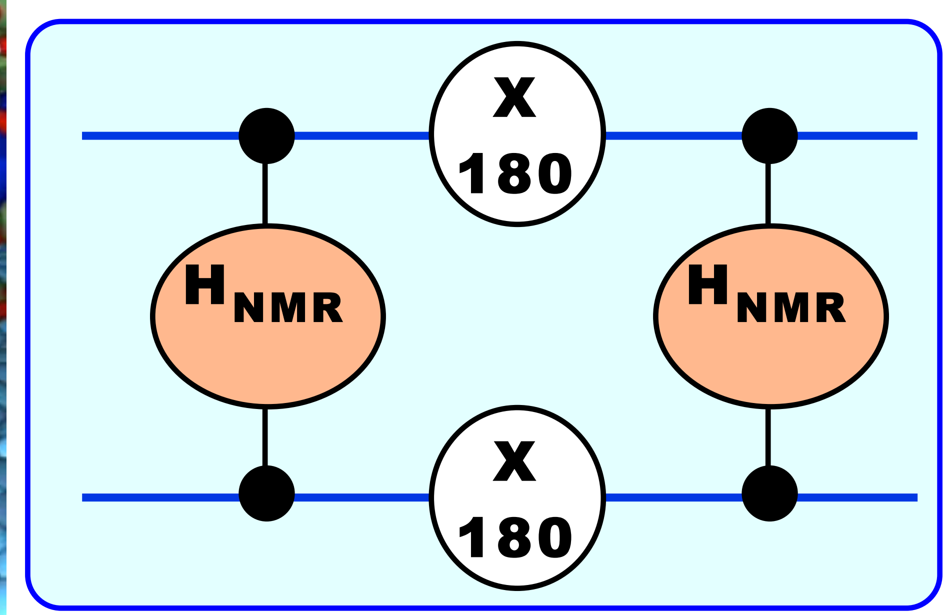
Physical Limits to (Quantum-) Information Processing





Physics of Information

"Information is physical"

Rolf Landauer
(1927-1999)

How fast can a computer be?

- Limited, e.g, by speed of light

How much power does it need?

- Cost for power, cooling requirements

How much information can it store / process ?

- Structure size, entropy, …

Physics of Information

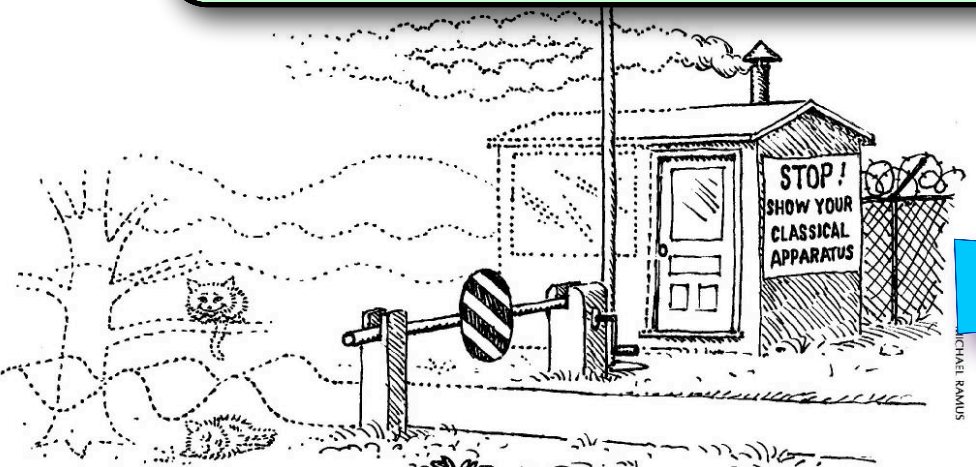
"Information is physical"

Rolf Landauer
(1927-1999)

At the fundamental level, nature must be described quantum mechanically

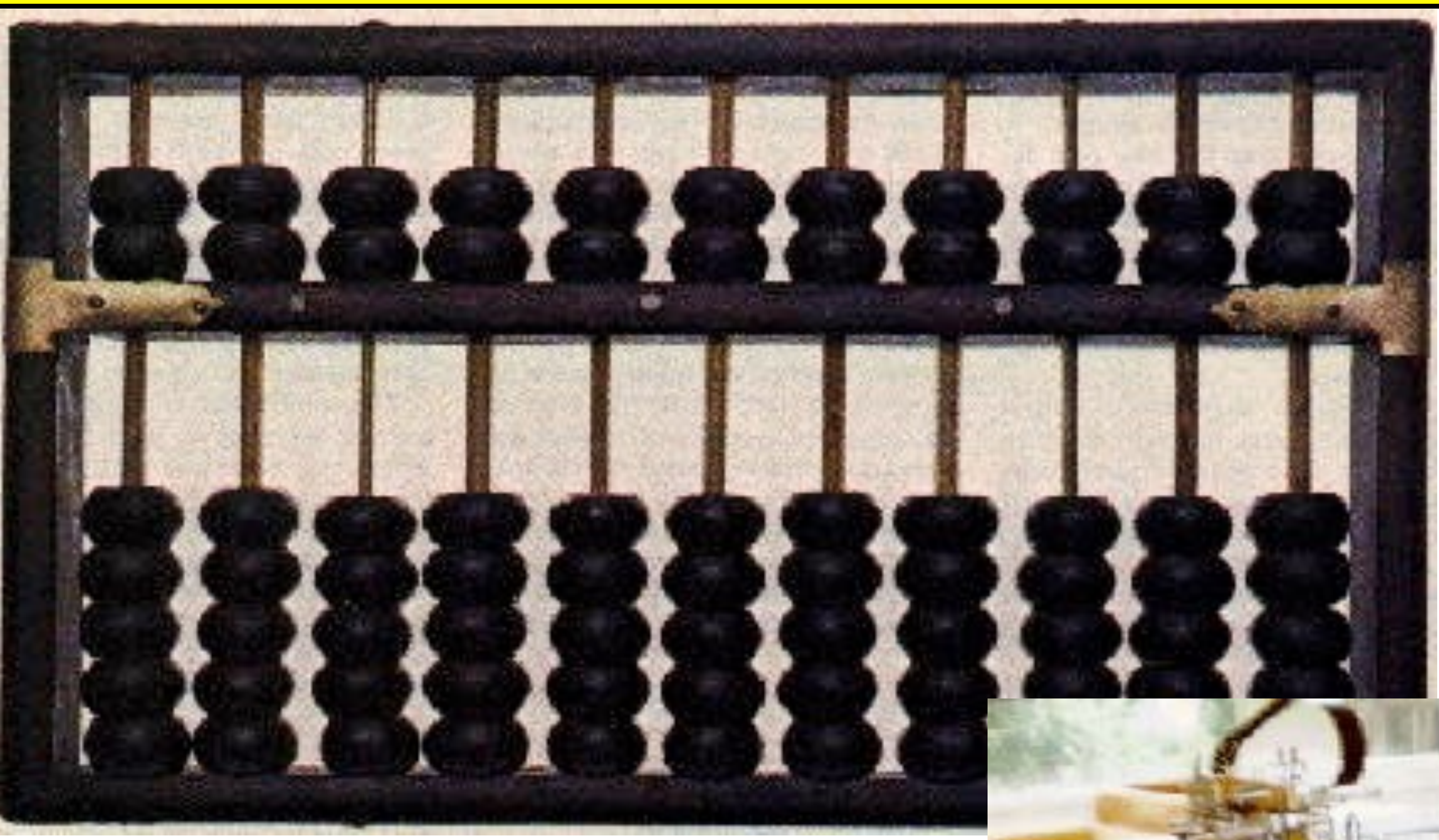
At the fundamental level, information science must be quantum mechanical

? Is it possible to exploit the quantum mechanical properties of information and information processing to obtain more powerful devices **?**

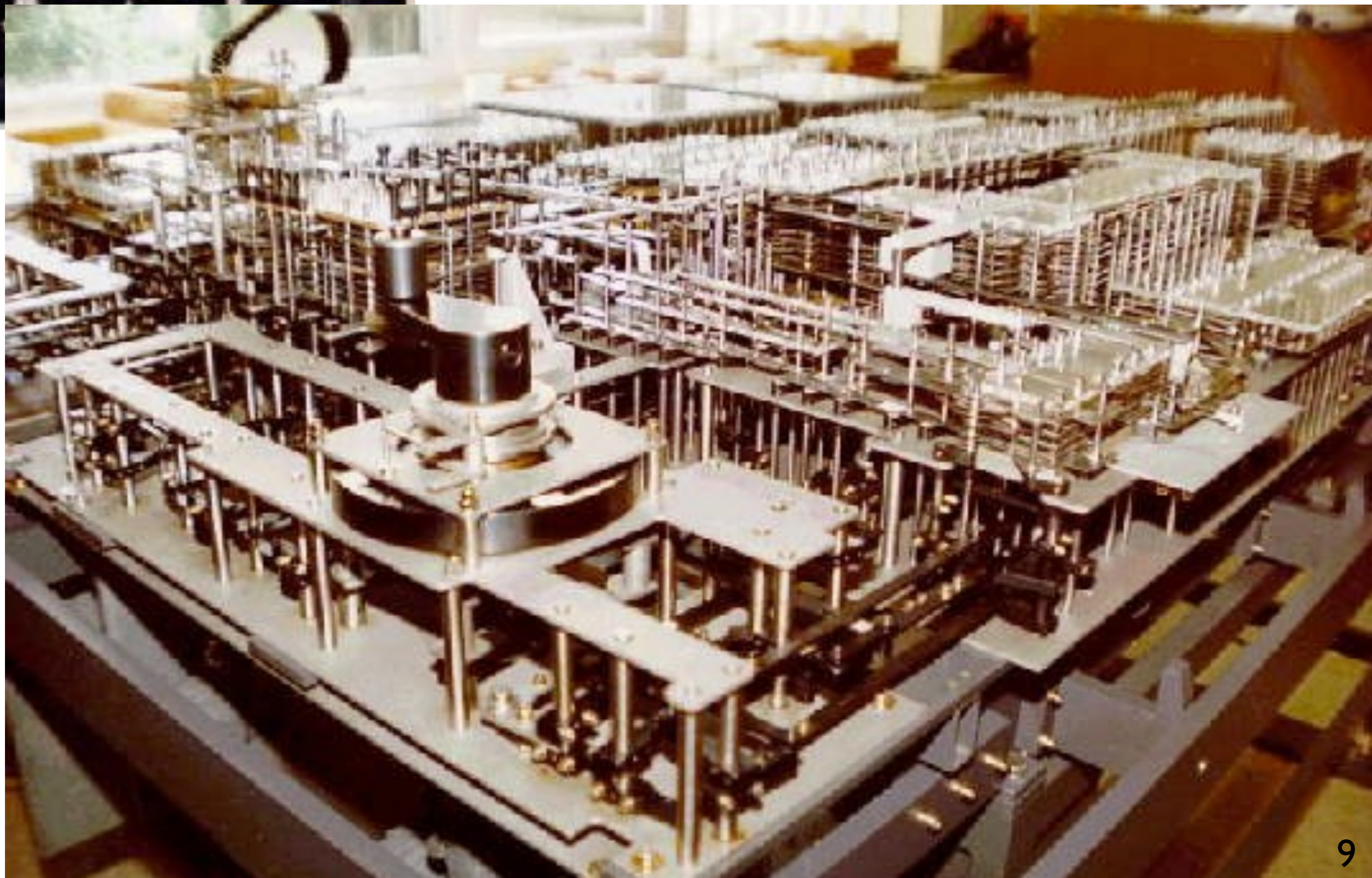


Quantum information processing
Quantum communication

Computers

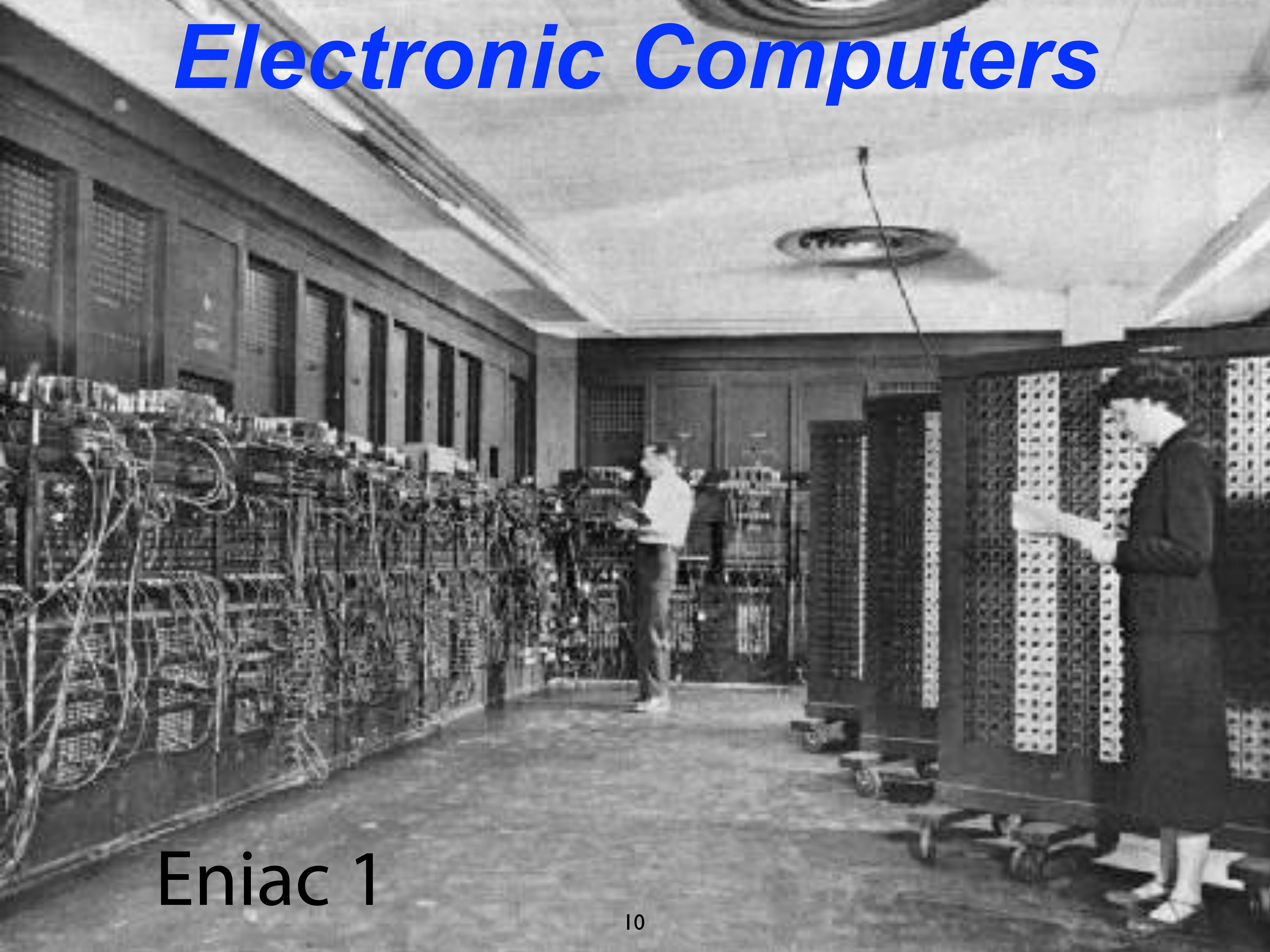


mechanical



electromechanical
programmable

Electronic Computers



Eniac 1

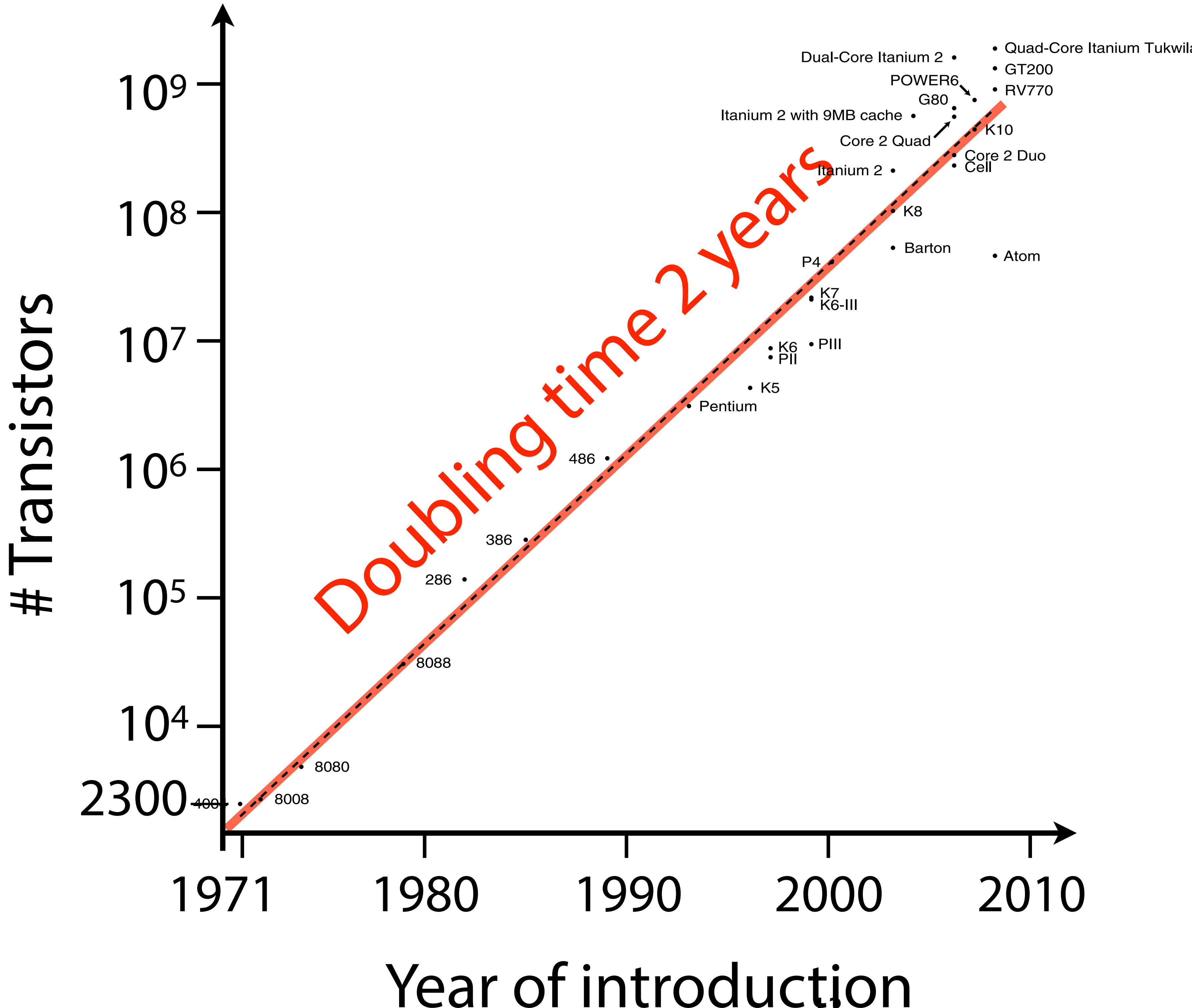
Minicomputer

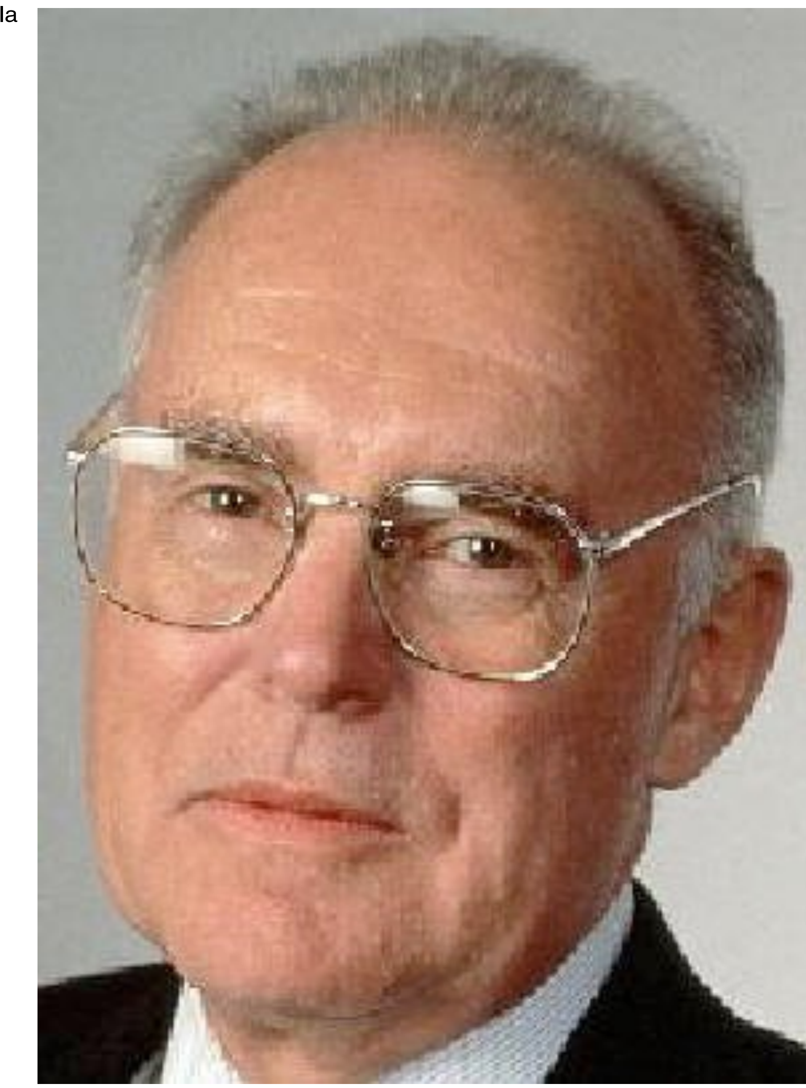
Higher Computational Power

How could this happen?

Exponential Growth

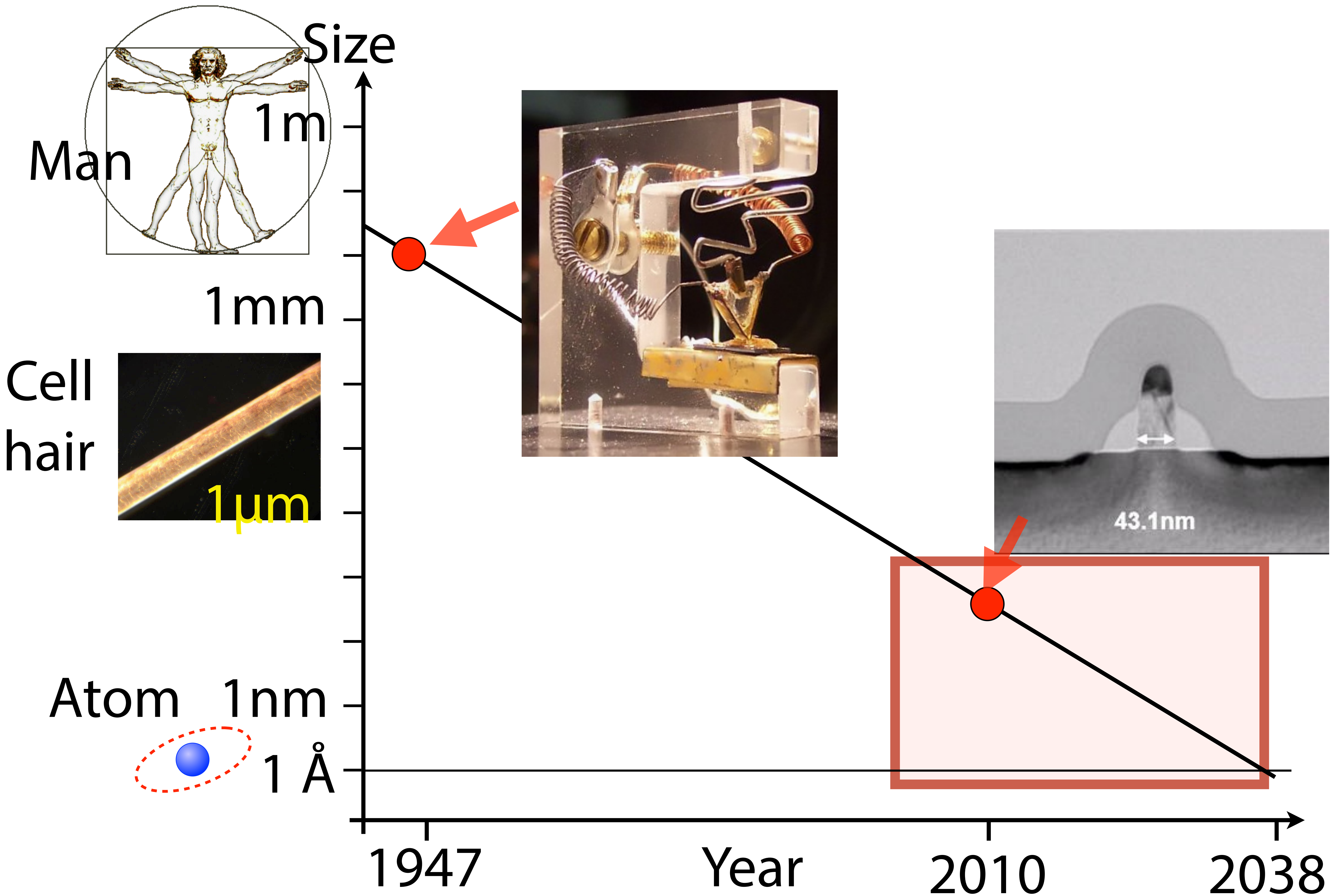
transistors on a chip grows exponentially



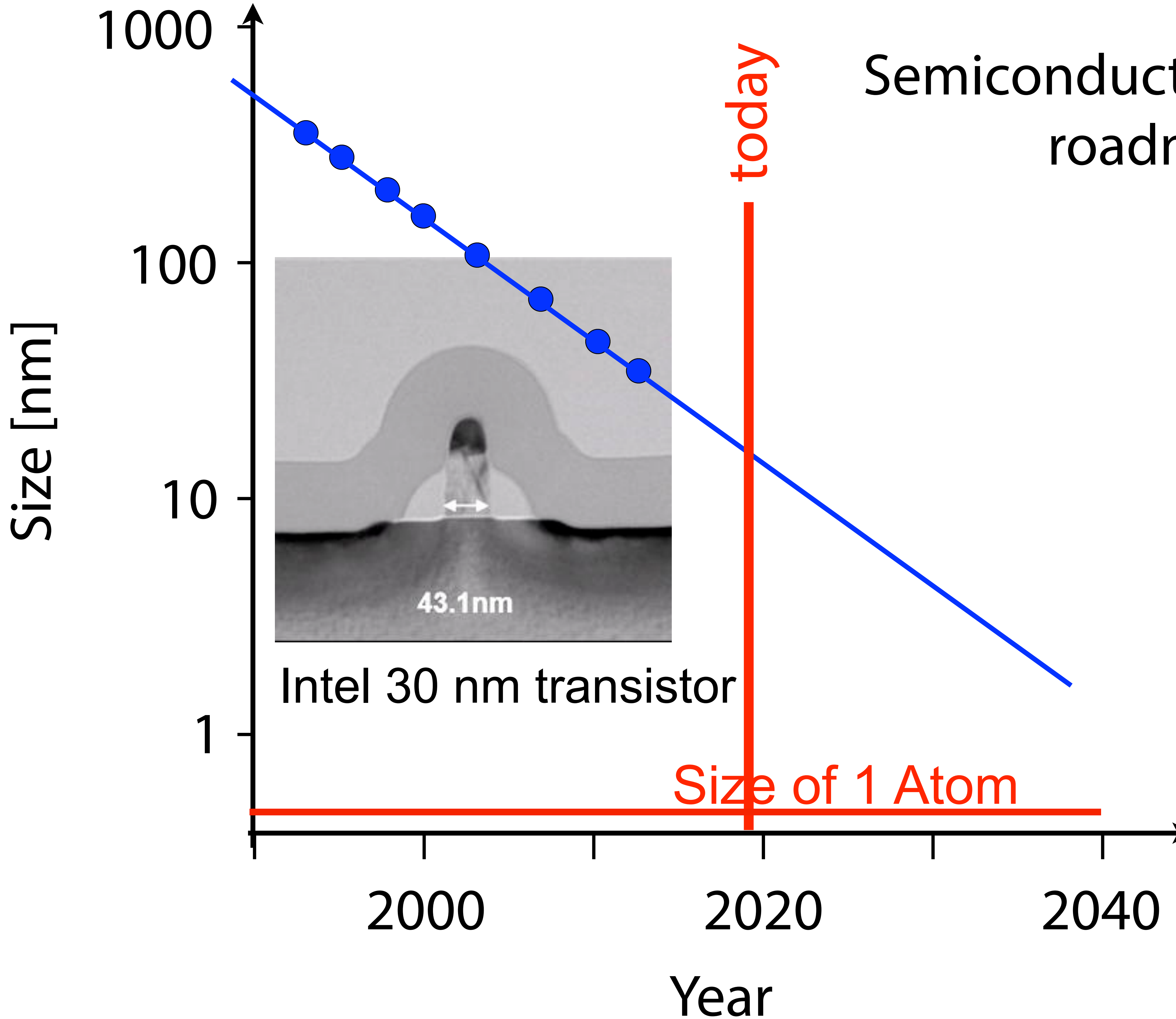


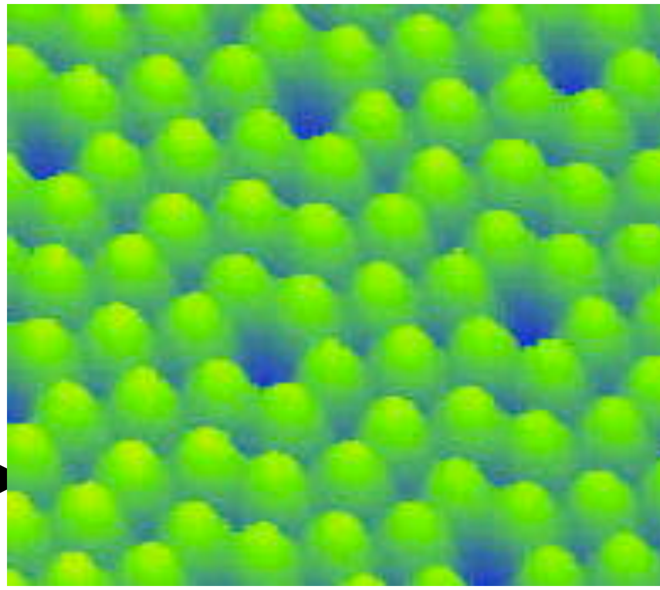
Gordon Moore

Size Scales

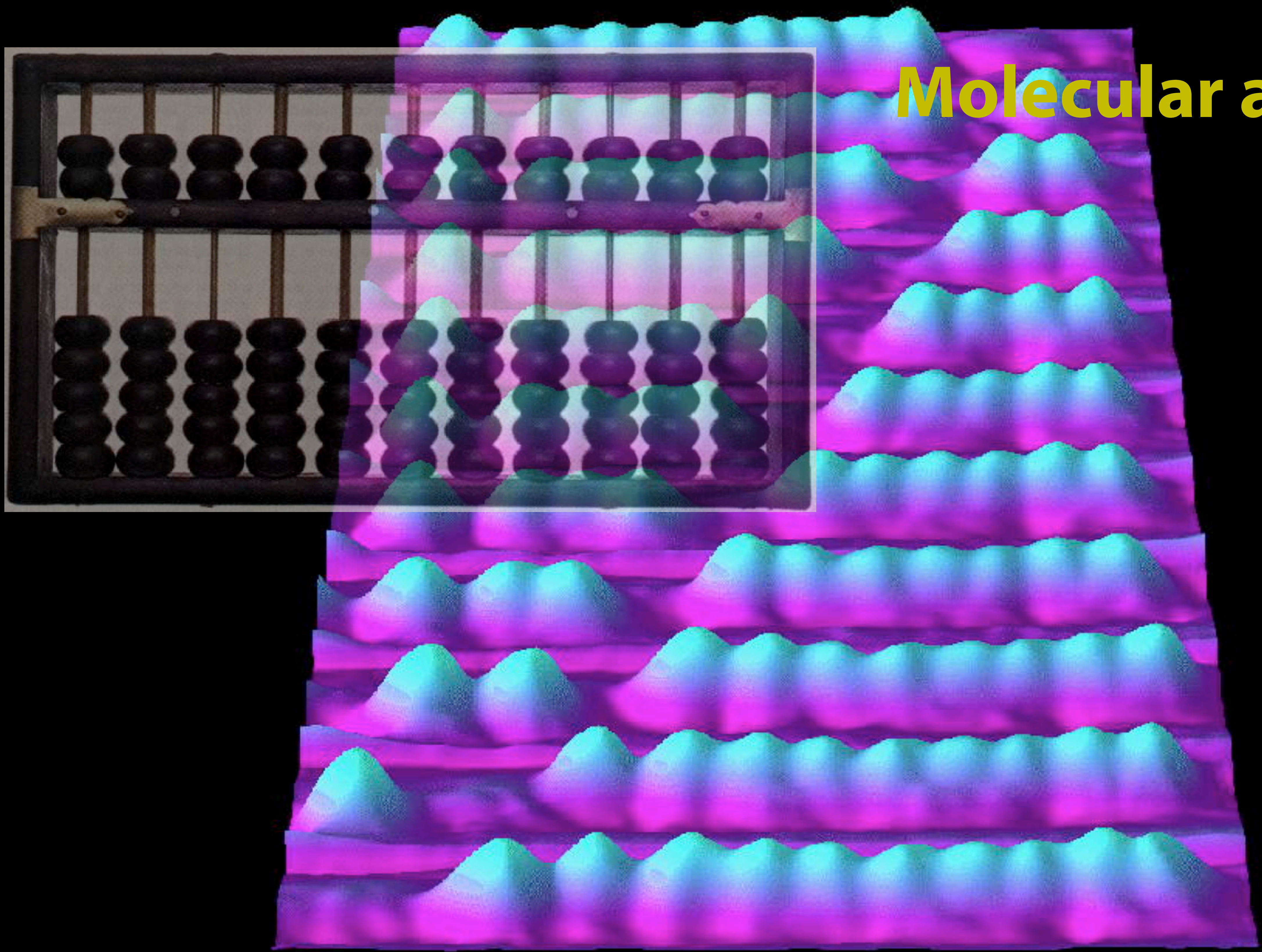

Size
Man
1m
1mm
Cell
hair
1µm
43.1nm
Atom
1nm
1 Å
1947
Year
2010
2038

The Shrinking Transistor



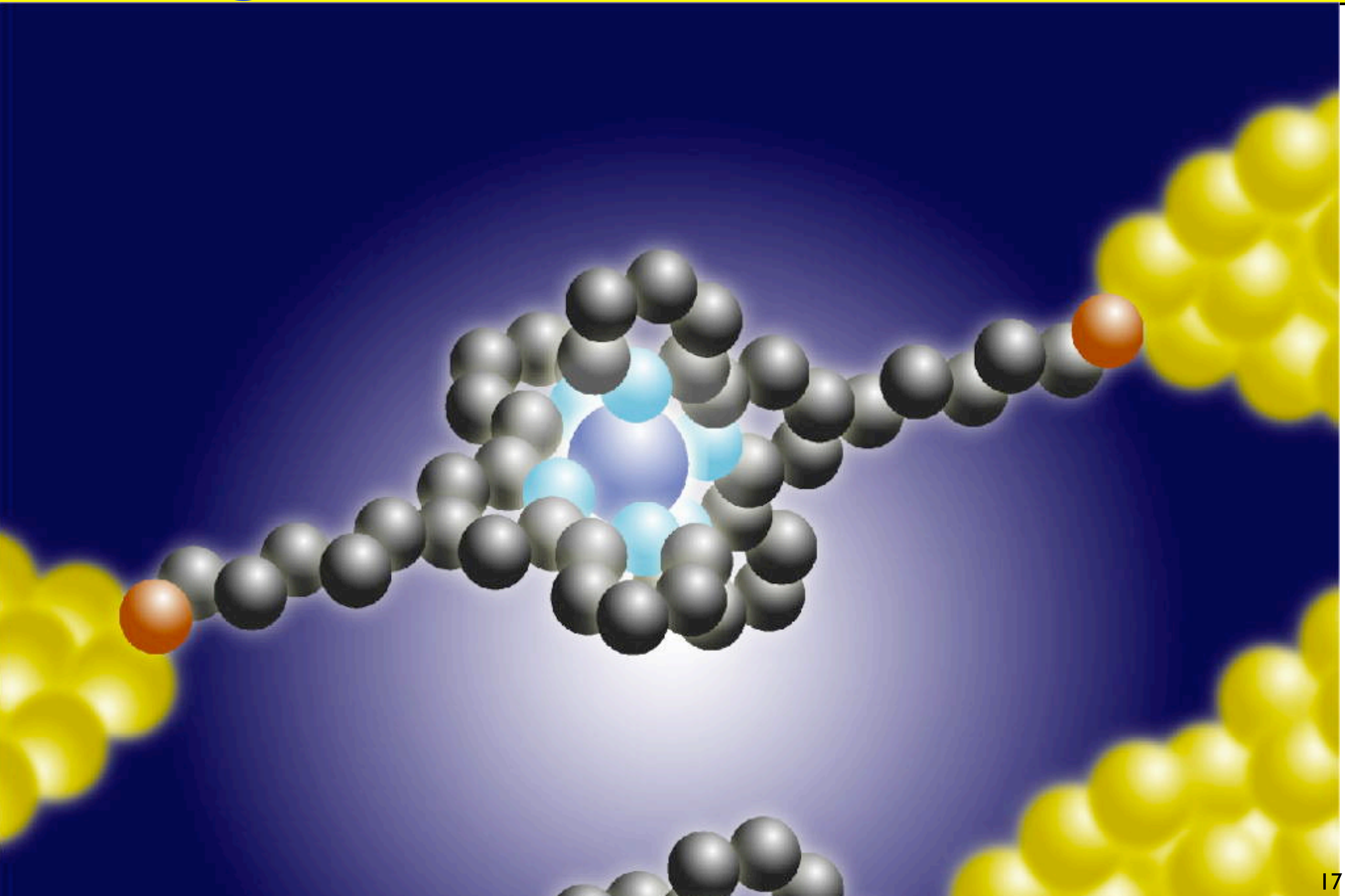


The Smallest Computer Yet

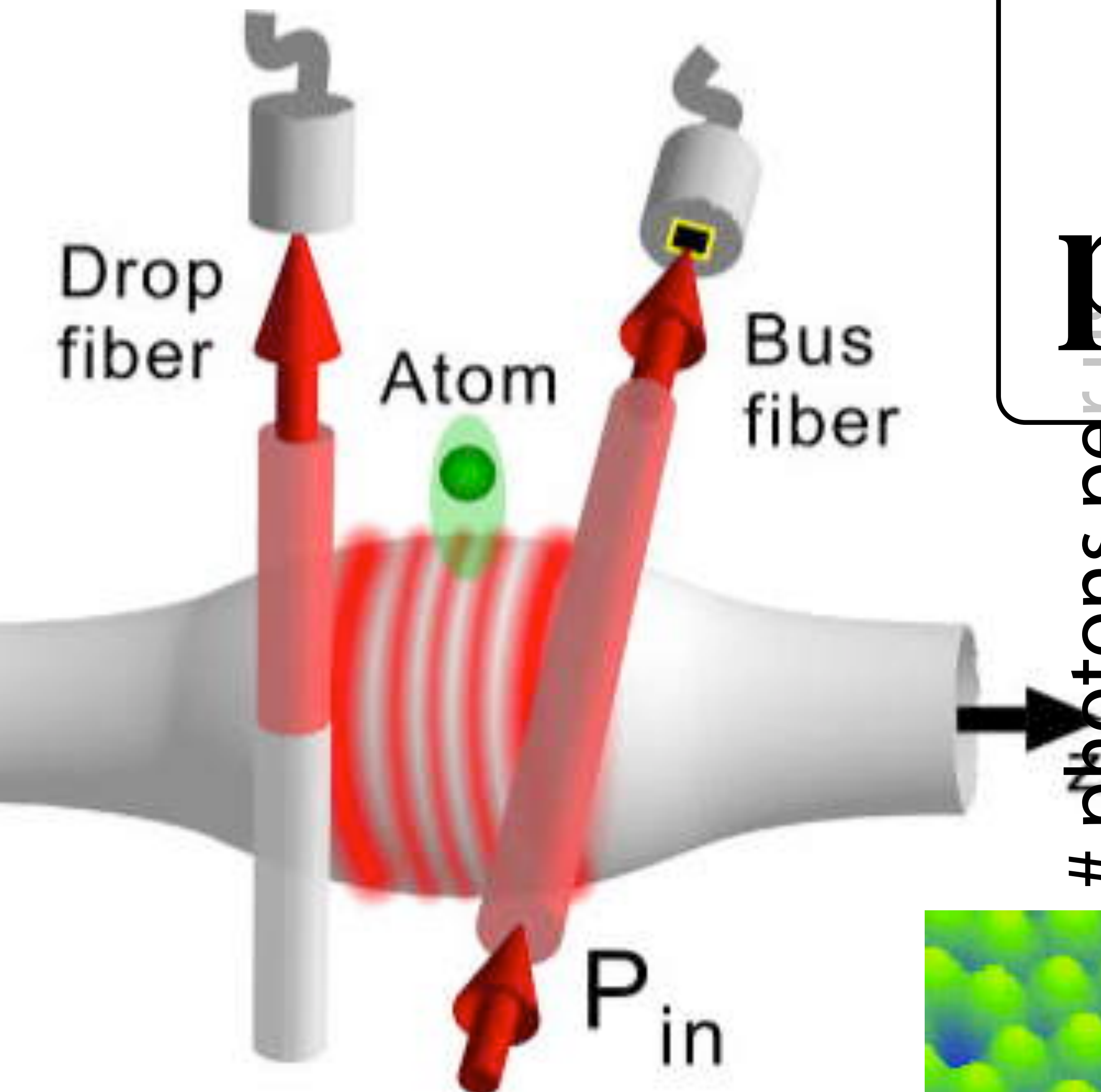


C_{60} molecules on Si, IBM Zürich

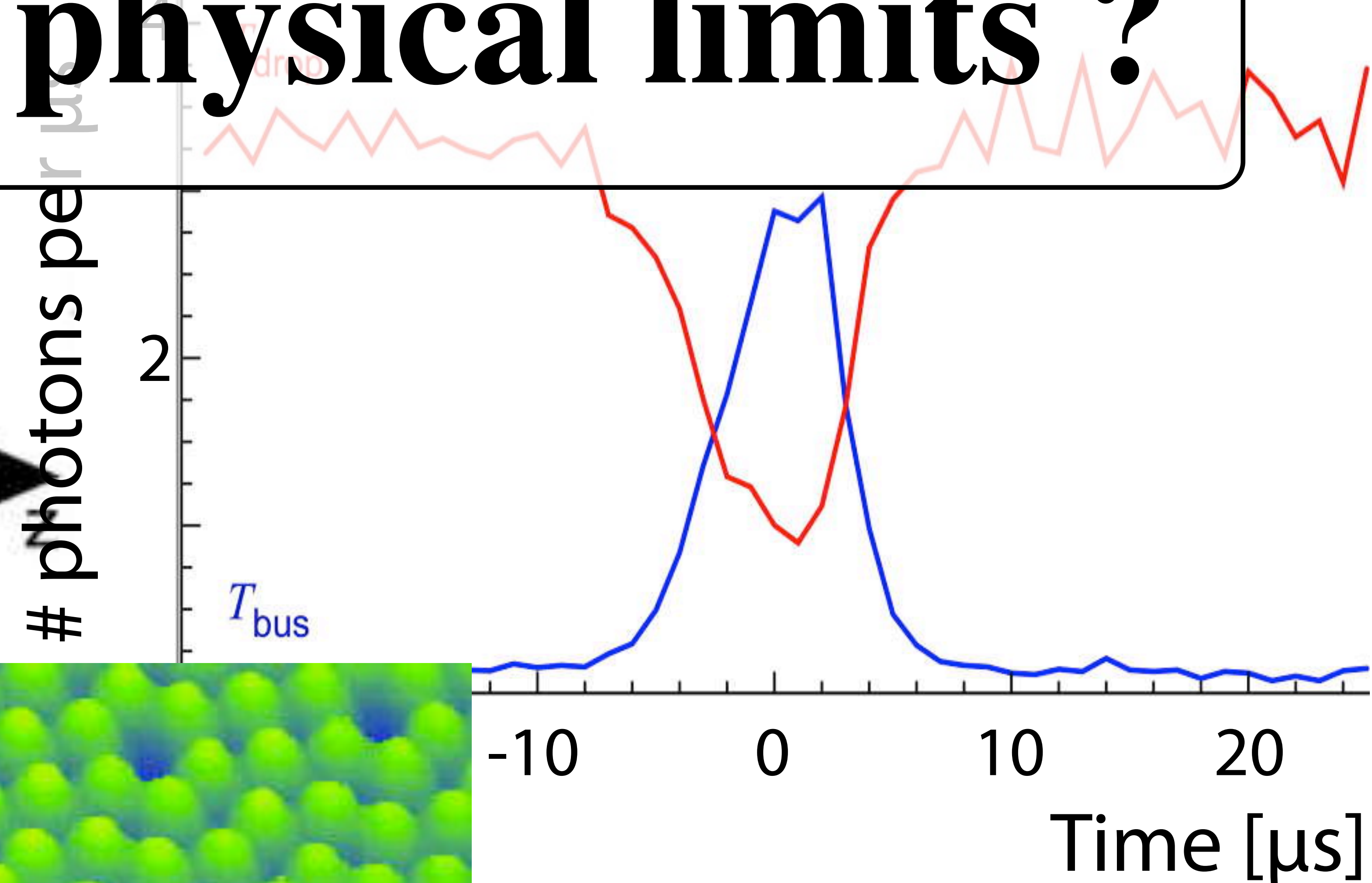
Single Molecule Transistor

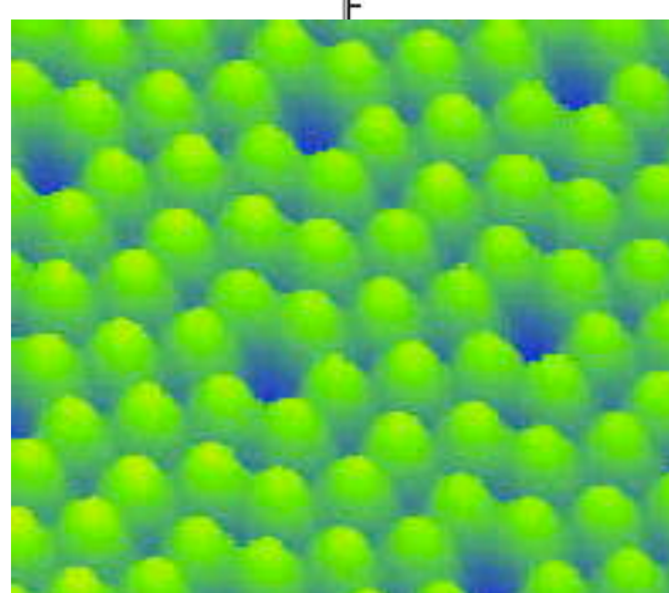


1 Atom - Switch



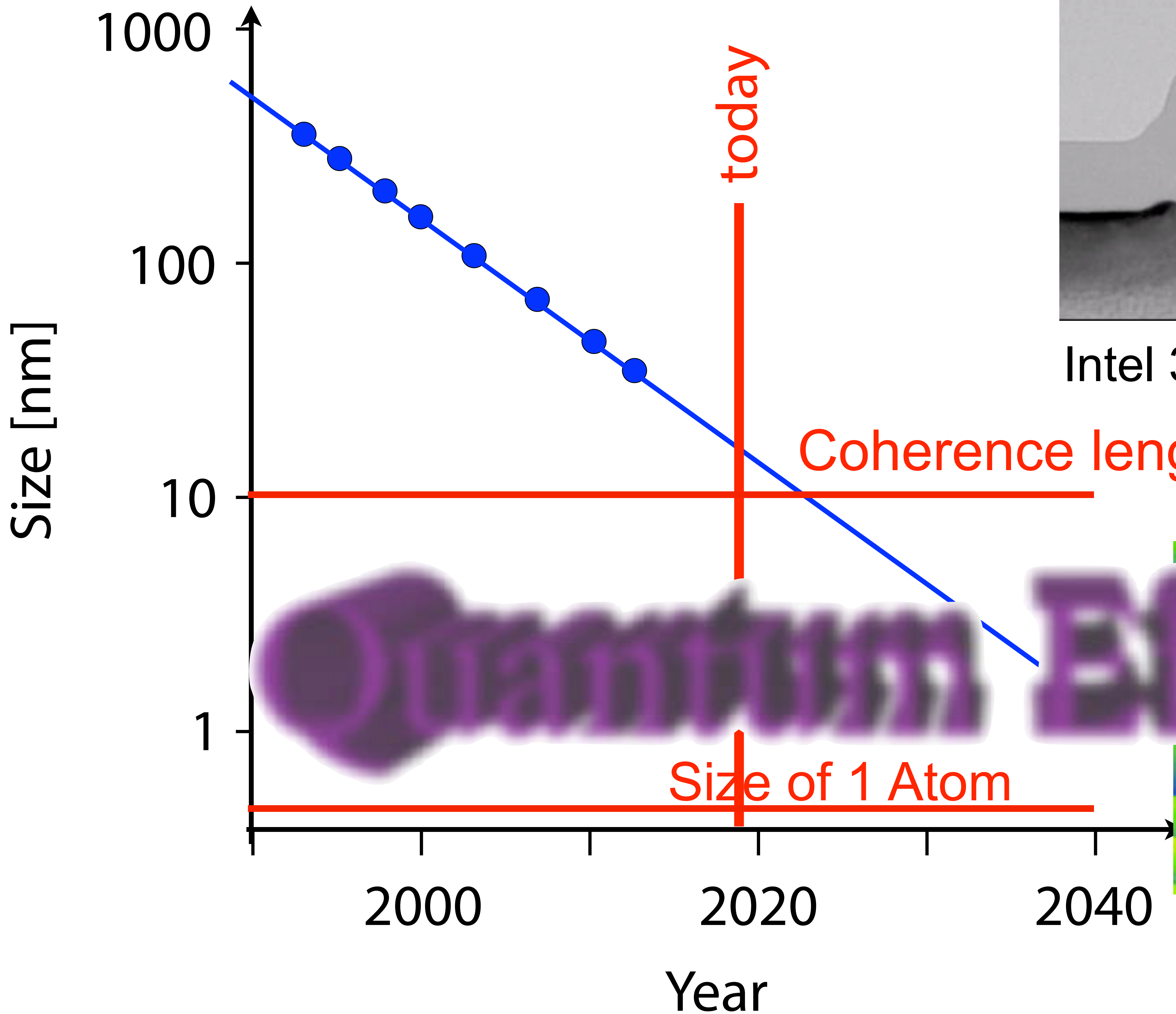
Where are the physical limits ?

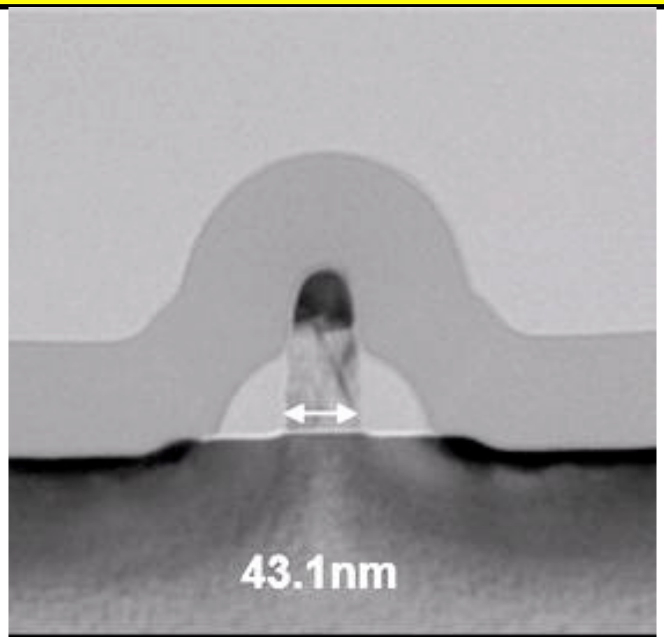




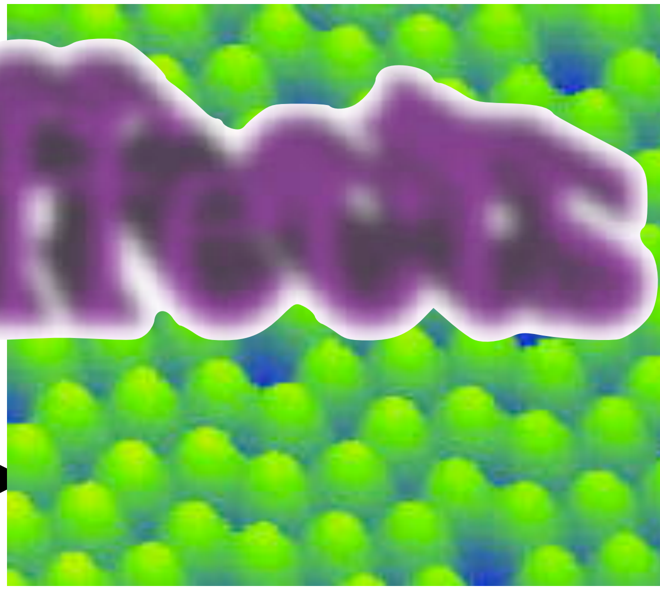
Phys. Rev. Lett. <u>111</u>, 193601 (2013).

The Shrinking Transistor





Intel 30 nm transistor

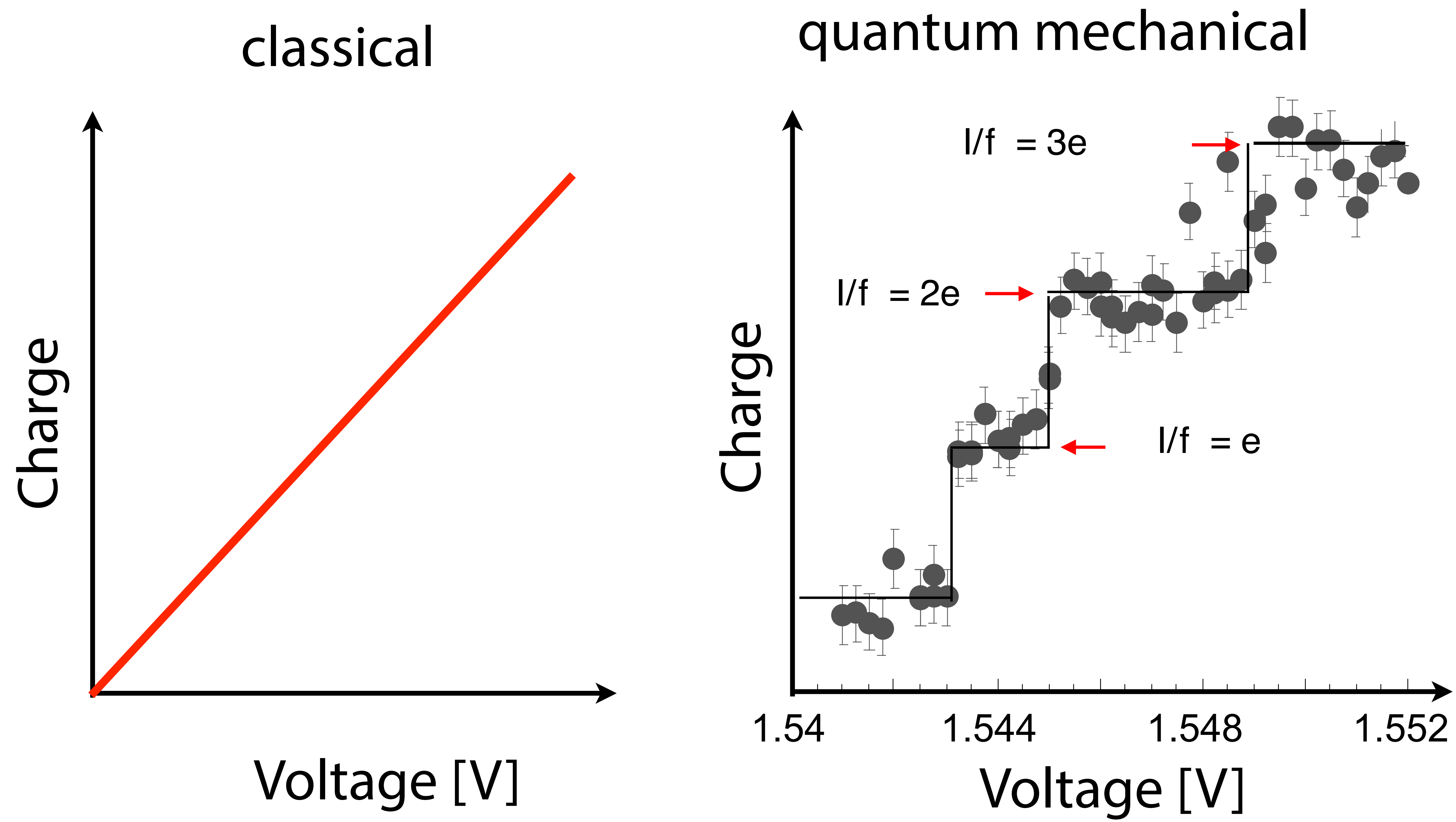


Particles and Waves

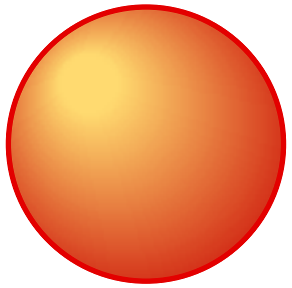
STM image of
Fe atoms on Cu

Charge Quantization

Electronic circuits behave qualitatively different when their size approaches atomic dimensions.



Small Capacitors



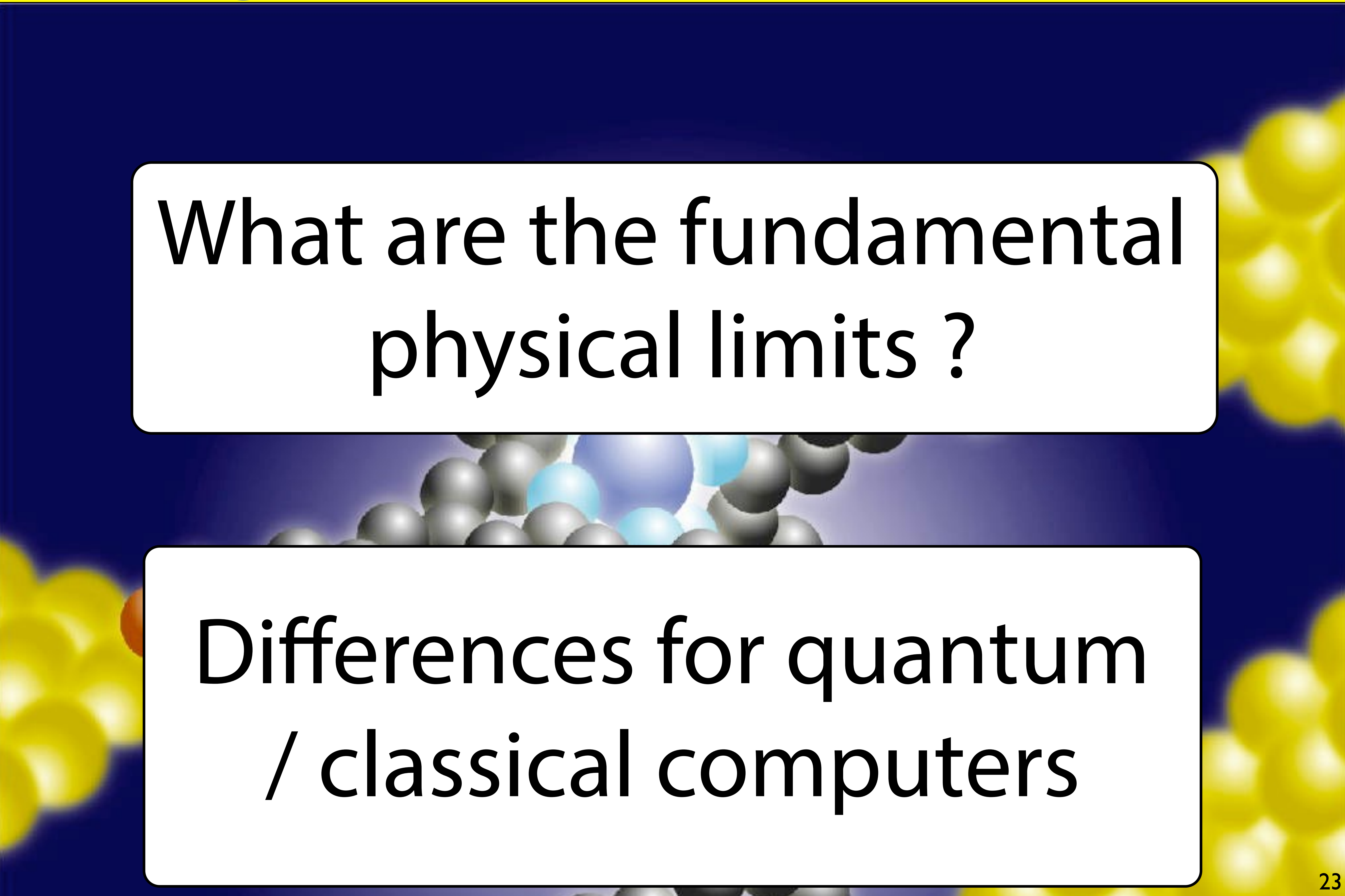
Model: spherical capacitor, radius *r*

Capacitance $C = 4\pi\epsilon_0 r$

Example: $r = 5$ nm → $C = 5.5 \cdot 10^{-19}$ F

Voltage change of 1 V moves 3.4 electrons

Single Molecule Transistor



What are the fundamental physical limits ?

Differences for quantum / classical computers

Information and Physics

Every computational process proceeds in a physical system

Input

0 0 1 1 0 1 0

Computation

Physical process

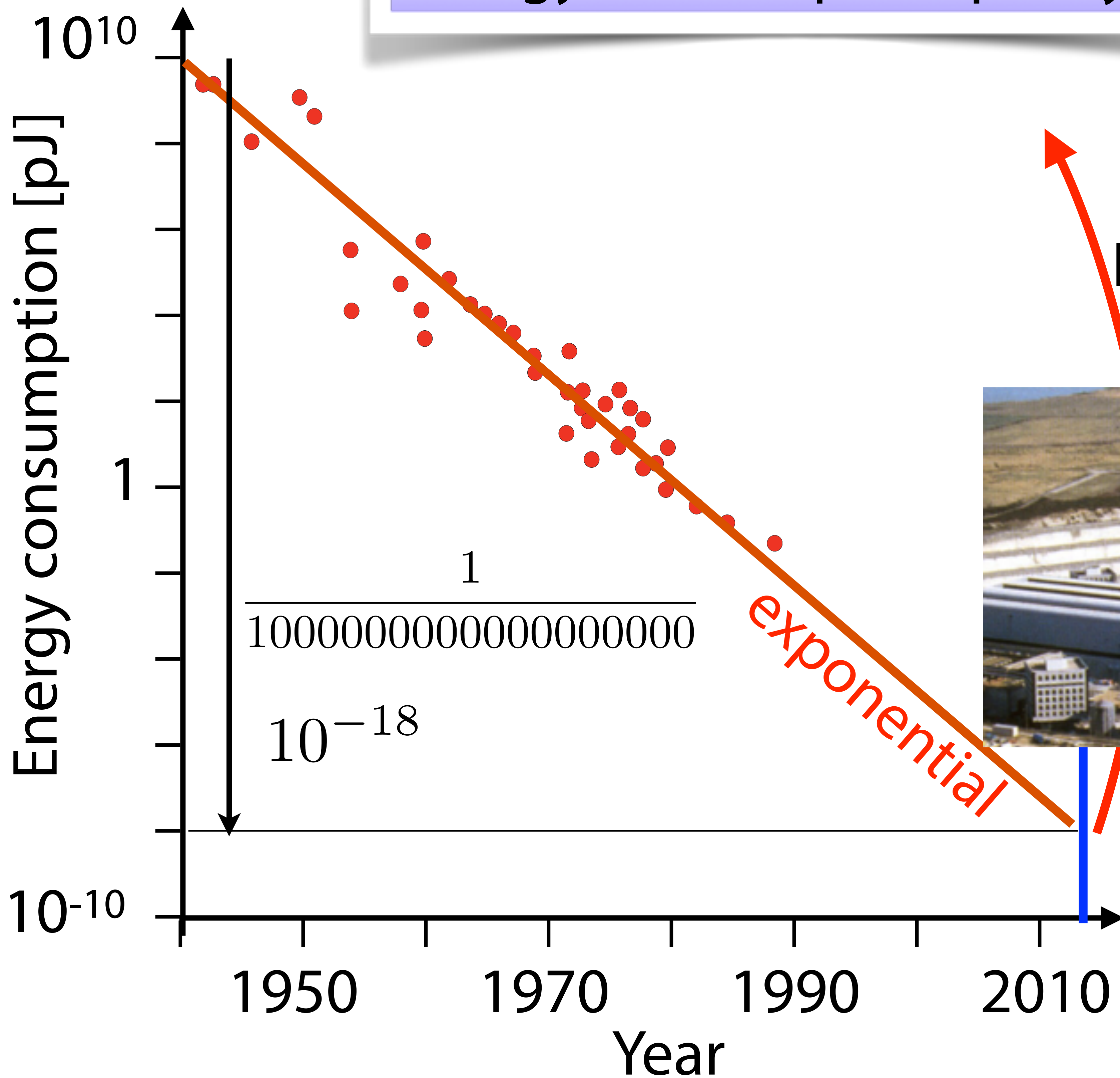
Output

Today’s computer use classical physics

“Classical Computers”

Energy Consumption

Energy consumption per cycle

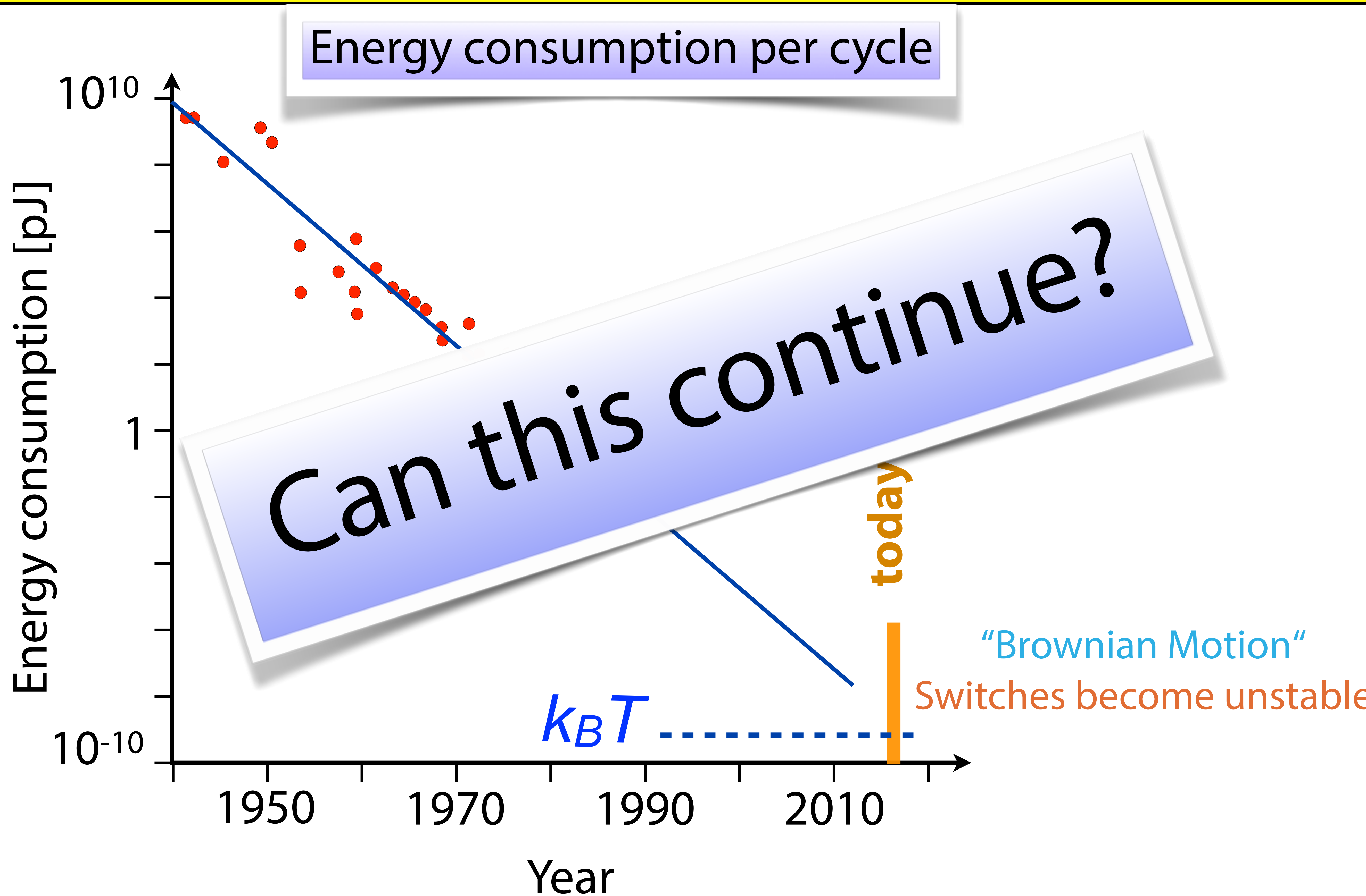


1 PC would consume
~10^{20} W = 10^{11} GW

Earth's surface covered with power stations

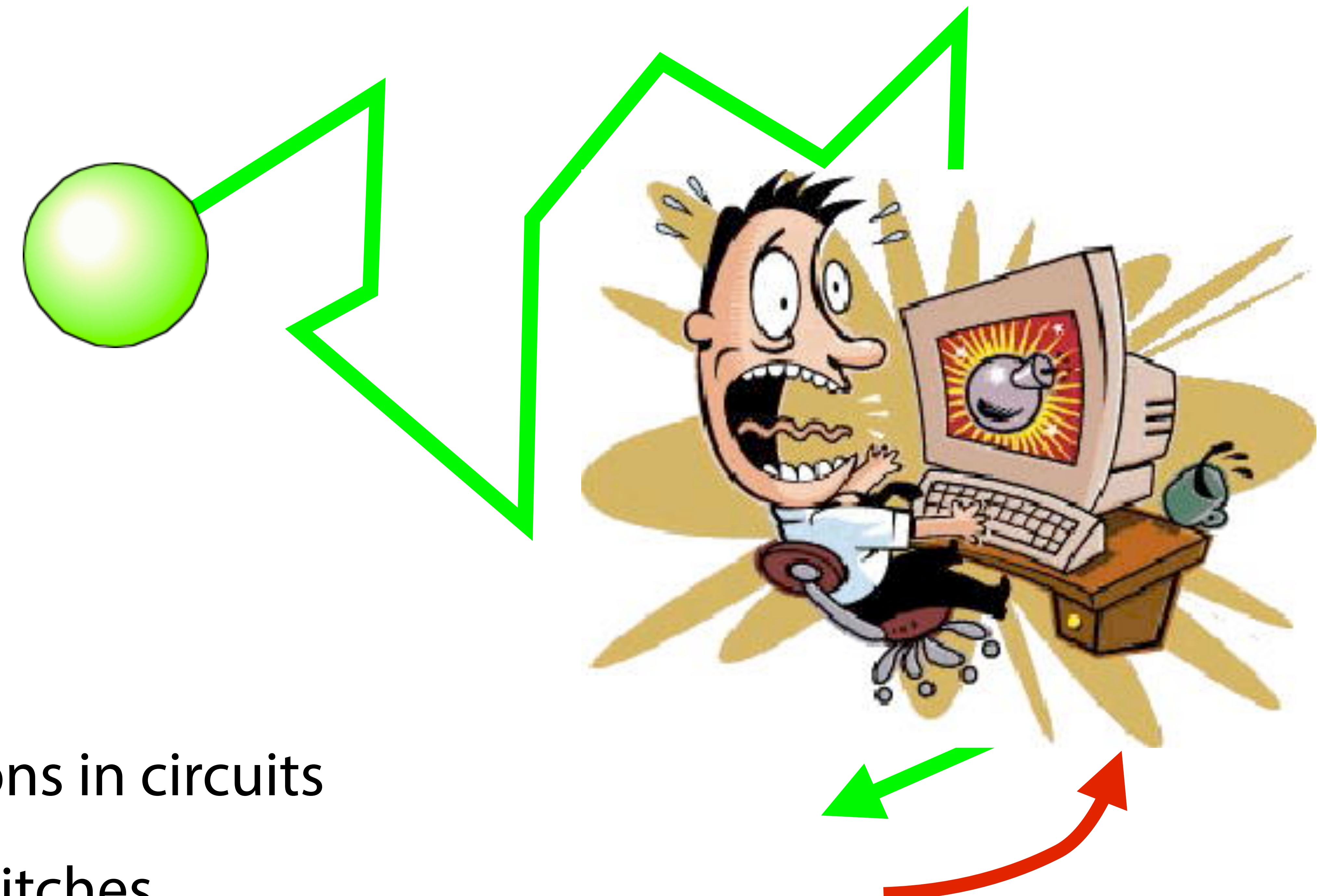
Distance 25 m

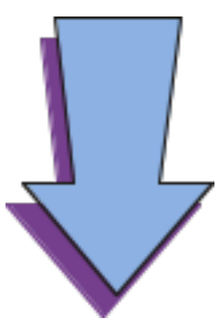
Cooler Computers



Brownian Motion

Random motion of particles

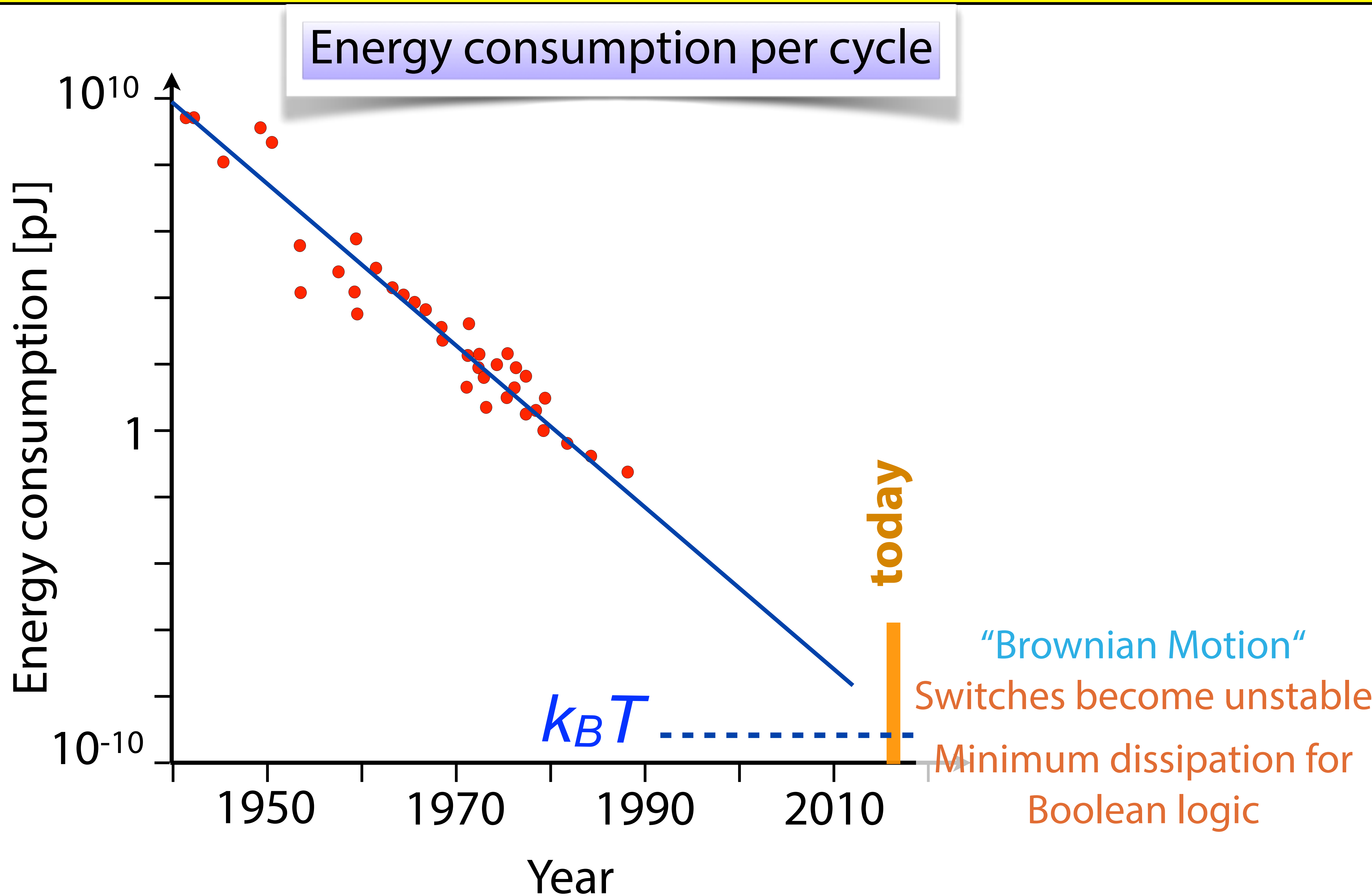




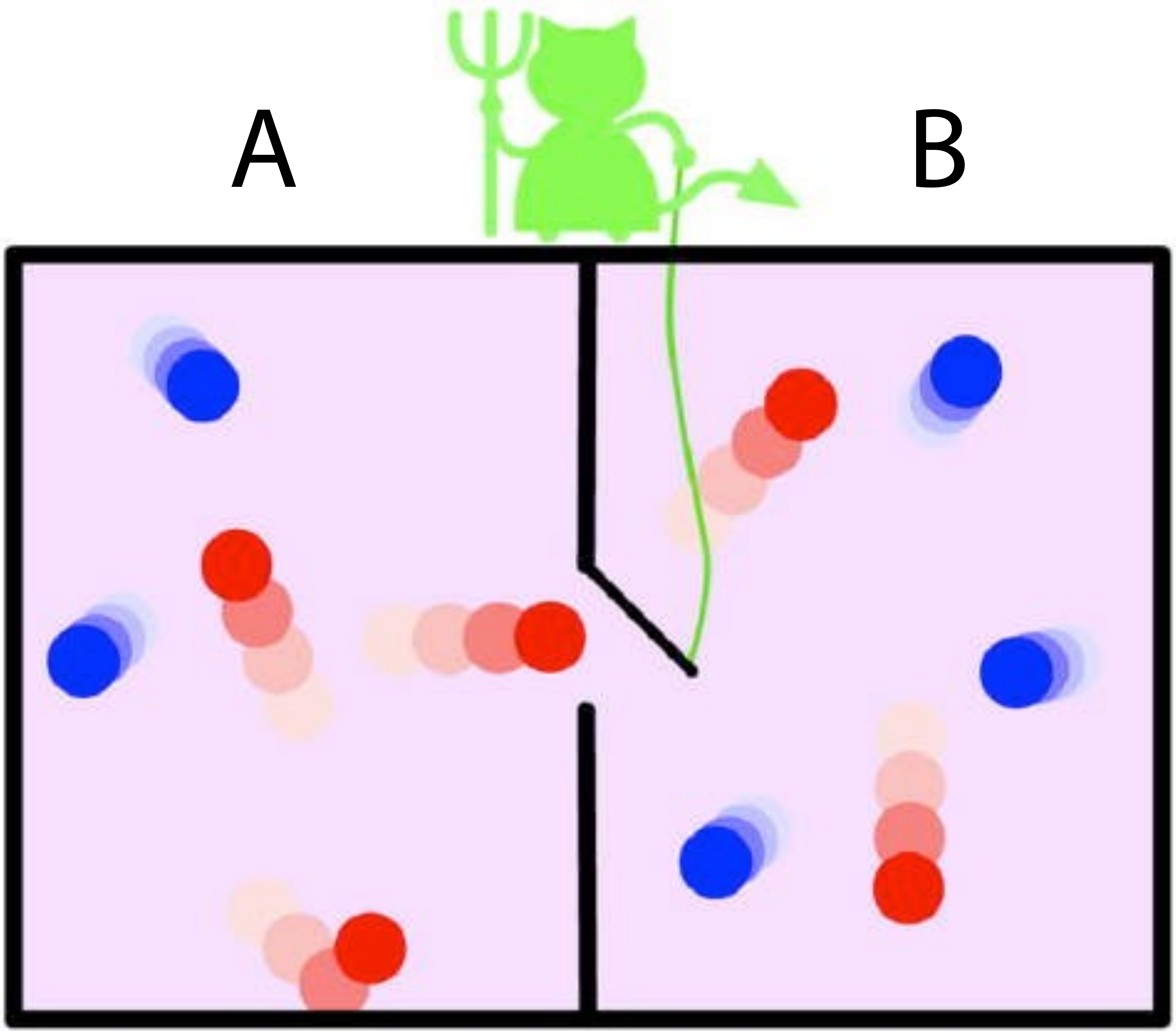
Also for electrons in circuits

May trigger switches

Cooler Computers



Maxwell' Demon

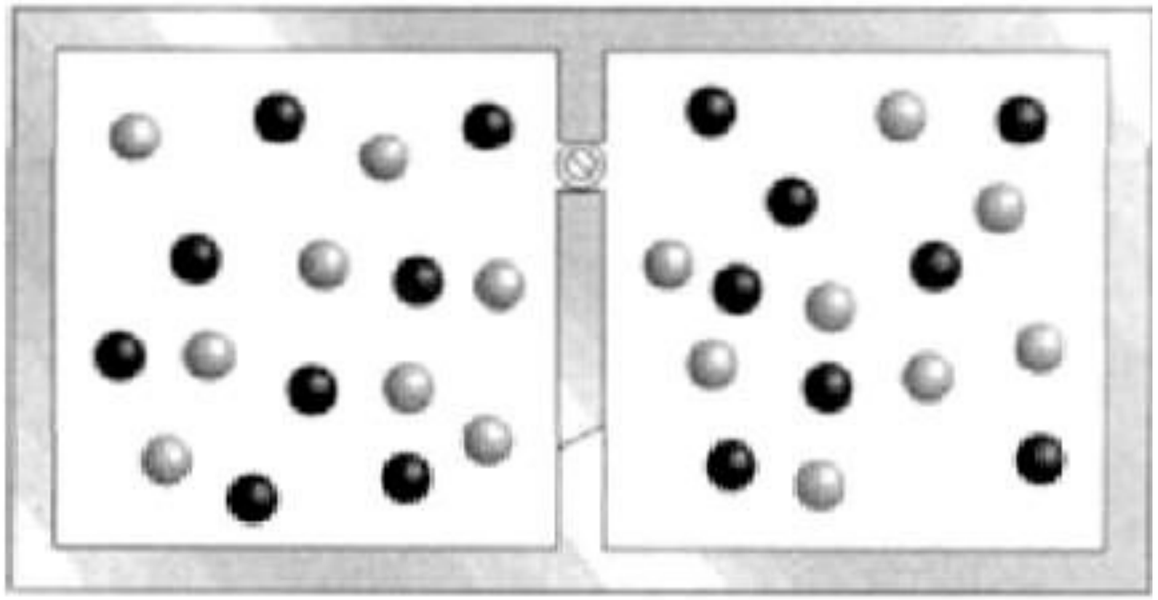


Maxwell’ Demon

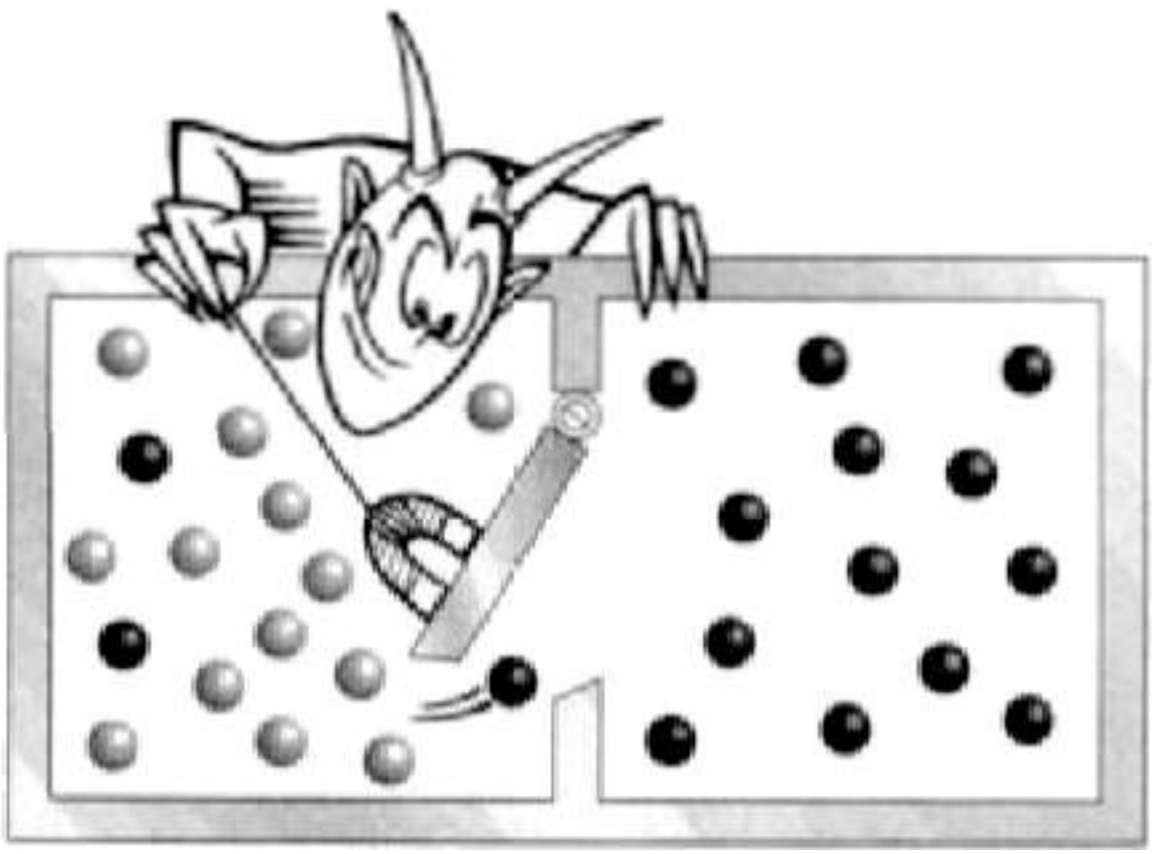
If we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being, whose attributes are still essentially finite as our own, would be able to do what is at present impossible to us. For we have seen that the molecules in a vessel full of air at uniform temperature are moving with velocities by no means uniform... Now let us suppose that such a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower one to pass from B to A. He will thus, without expenditure of work, raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics.

James Clark Maxwell, Theory of heat, 1871

Maxwell’ Demon



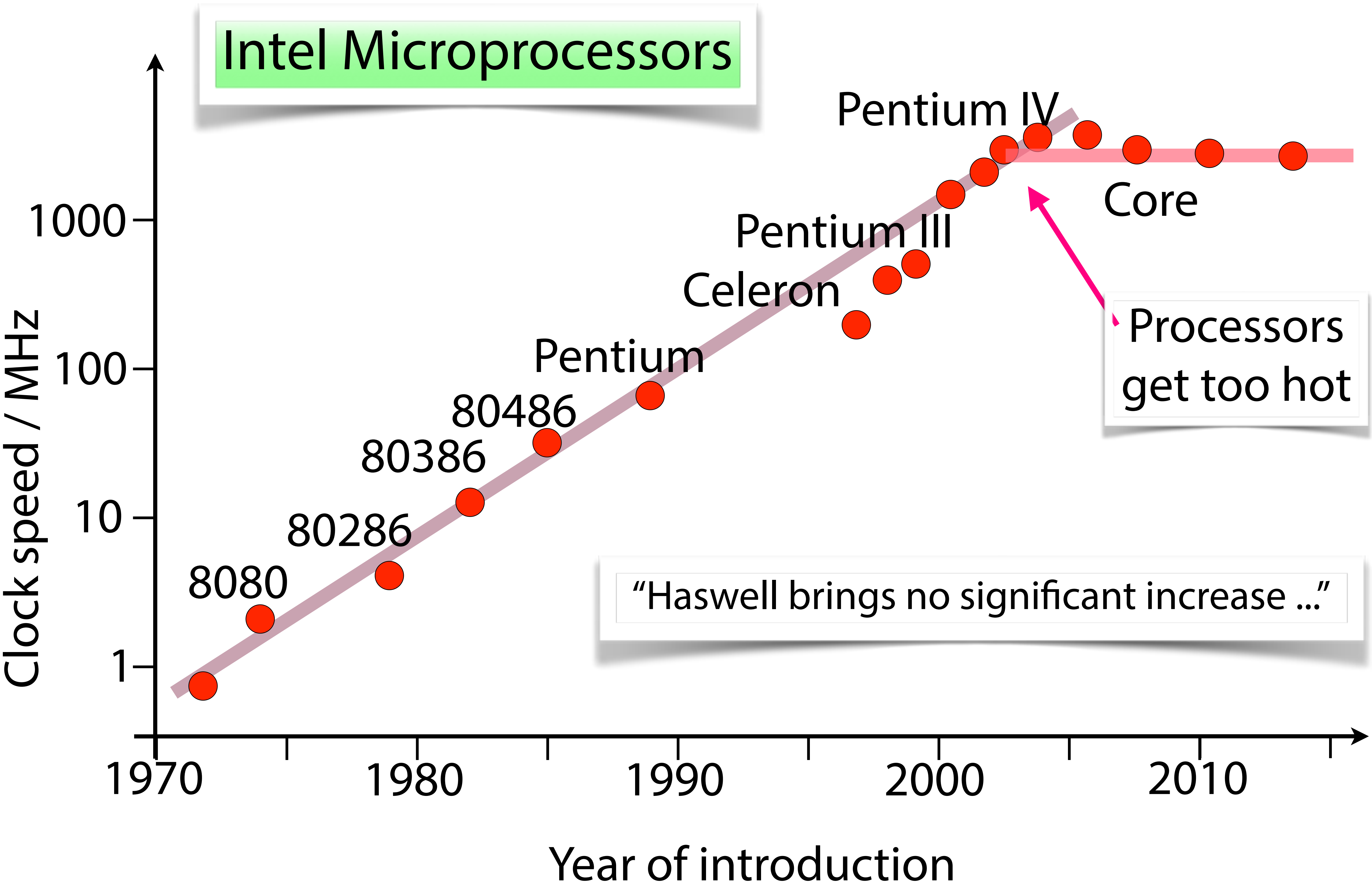
System at equilibrium



The demon and the friction-free trap door

System with lower entropy
Violation of the second law

Processor Speed



Quantum Effects

Size	de Broglie length
# Electrons	1
Energy	$k_B T$

Is there a limit ?

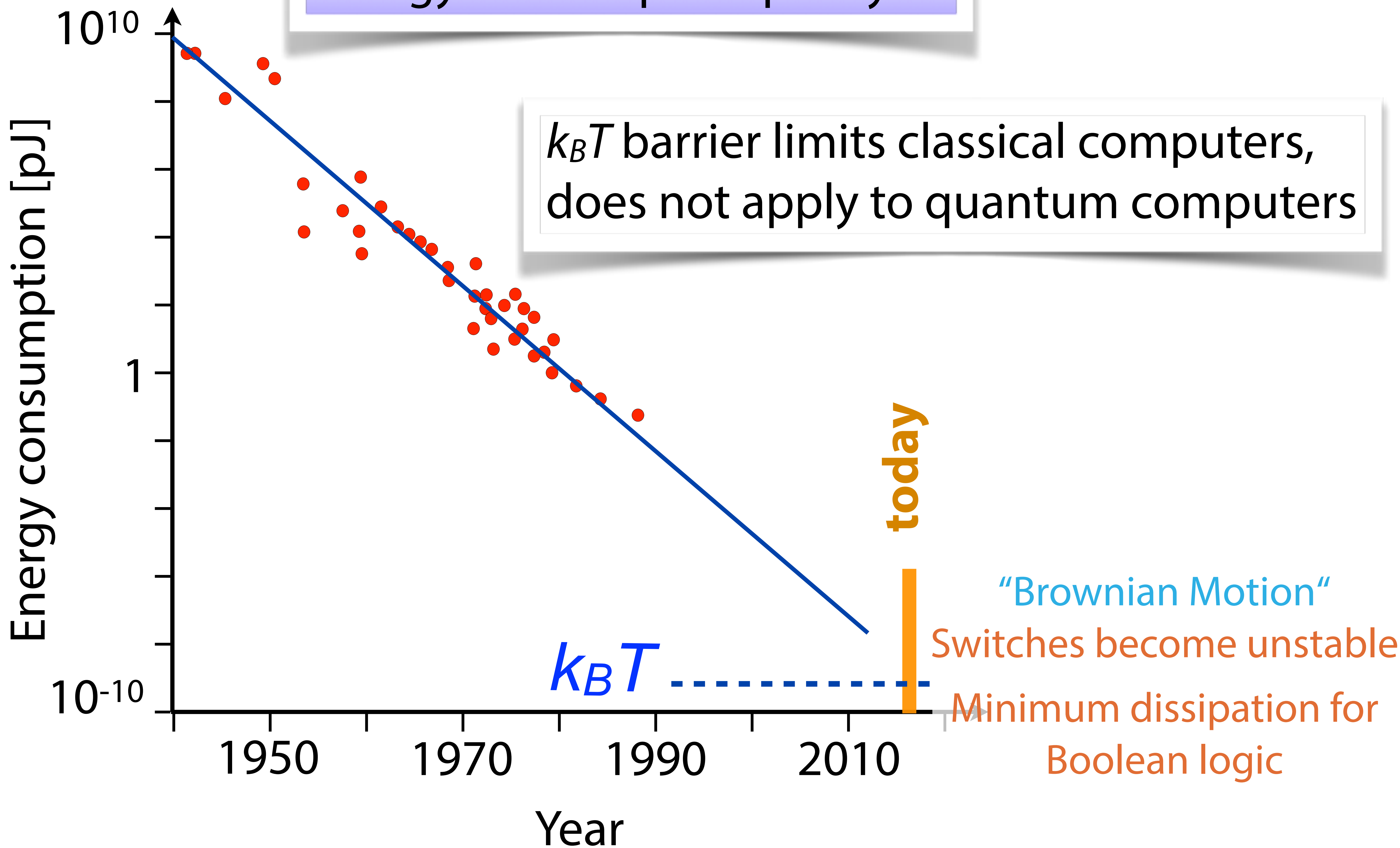
When quantum effects dominate

Will devices still work?
Are new concepts needed?

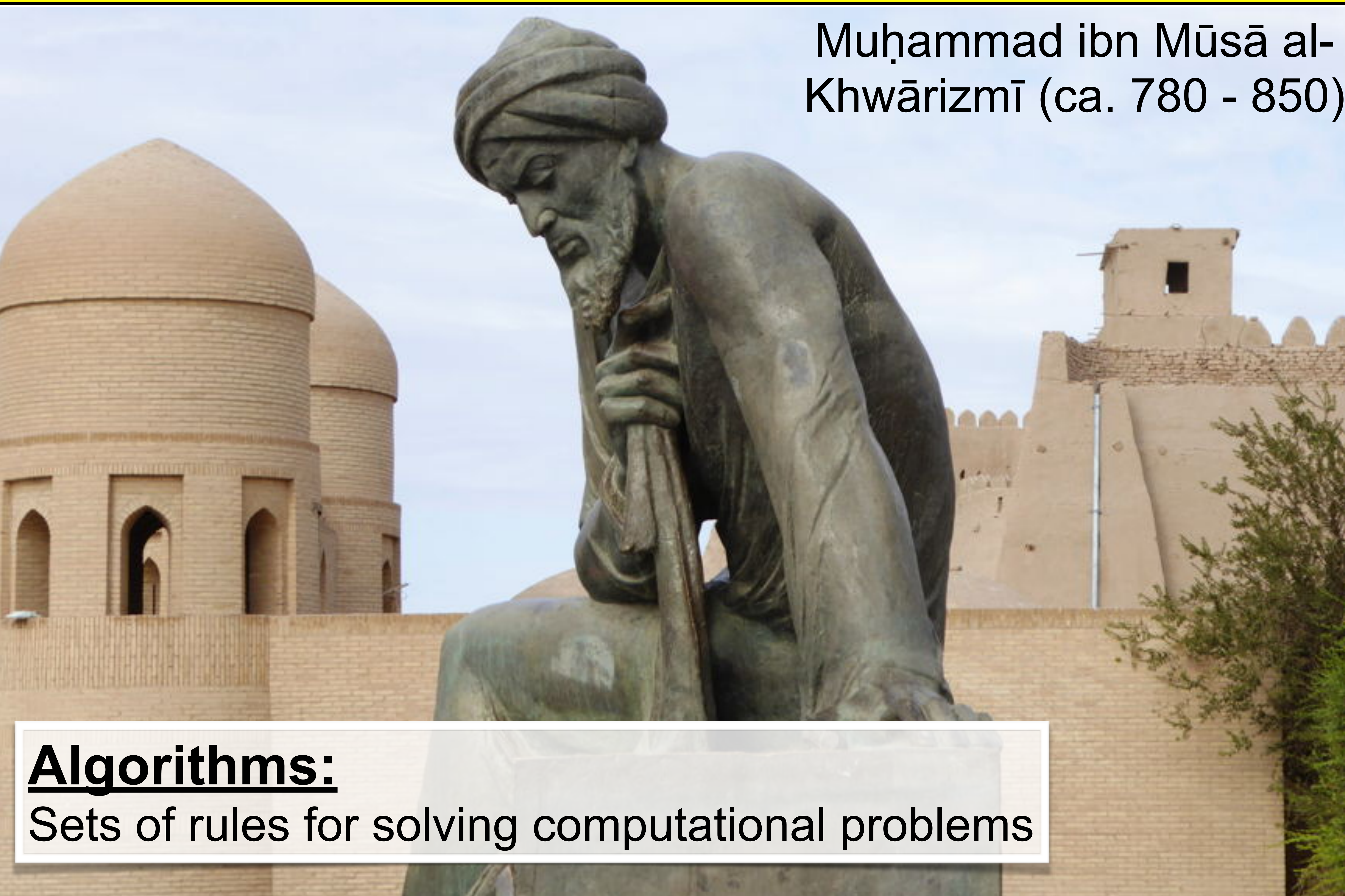
Cooler Computers

Energy consumption per cycle

$k_B T$ barrier limits classical computers, does not apply to quantum computers



Fundamental Computer Science



Muḥammad ibn Mūsā al-Khwārizmī (ca. 780 - 850)

Algorithms:

Sets of rules for solving computational problems

Church-Turing Hypothesis

One version:

"All computable functions are computable by Turing machine."

Alonzo Church. An unsolvable problem of elementary number theory. Am. J. Math., 58, 345–363 (1936).

Alan M. Turing. On computable numbers, with an application to the Entscheidungsproblem. Proc. Lond. Math. Soc. Ser., 42, 230 (1936). See also ibidem 43, 544.

Computable: algorithm exists that terminates

Efficiently computable: Resources scale at most polynomially with the size of the problem

Simple Computations

$1+1$

$5 \cdot 7$

$3945 / 789$

$987654321 \cdot 123456789$

Simple:

- There is an algorithm
- Execution time does not increase too rapidly if the numbers increase

Abu Dscha'far Muhammad ibn Musa al-Chwarizmi (780-850)

Difficult Tasks

Prime factors of $15 = \boxed{3} \cdot \boxed{5}$

$77 = \boxed{7} \cdot \boxed{11}$

$7031 = \boxed{79} \cdot \boxed{89}$

$1092001 = \boxed{677} \cdot \boxed{1613}$

Decomposition : hard

Multiplication : easy

Difficult:

- Computing time grows exponentially with the size of the input

Application public key cryptography:

Decryption without private key ~ decomposition

Decryption with private key ~ multiplication

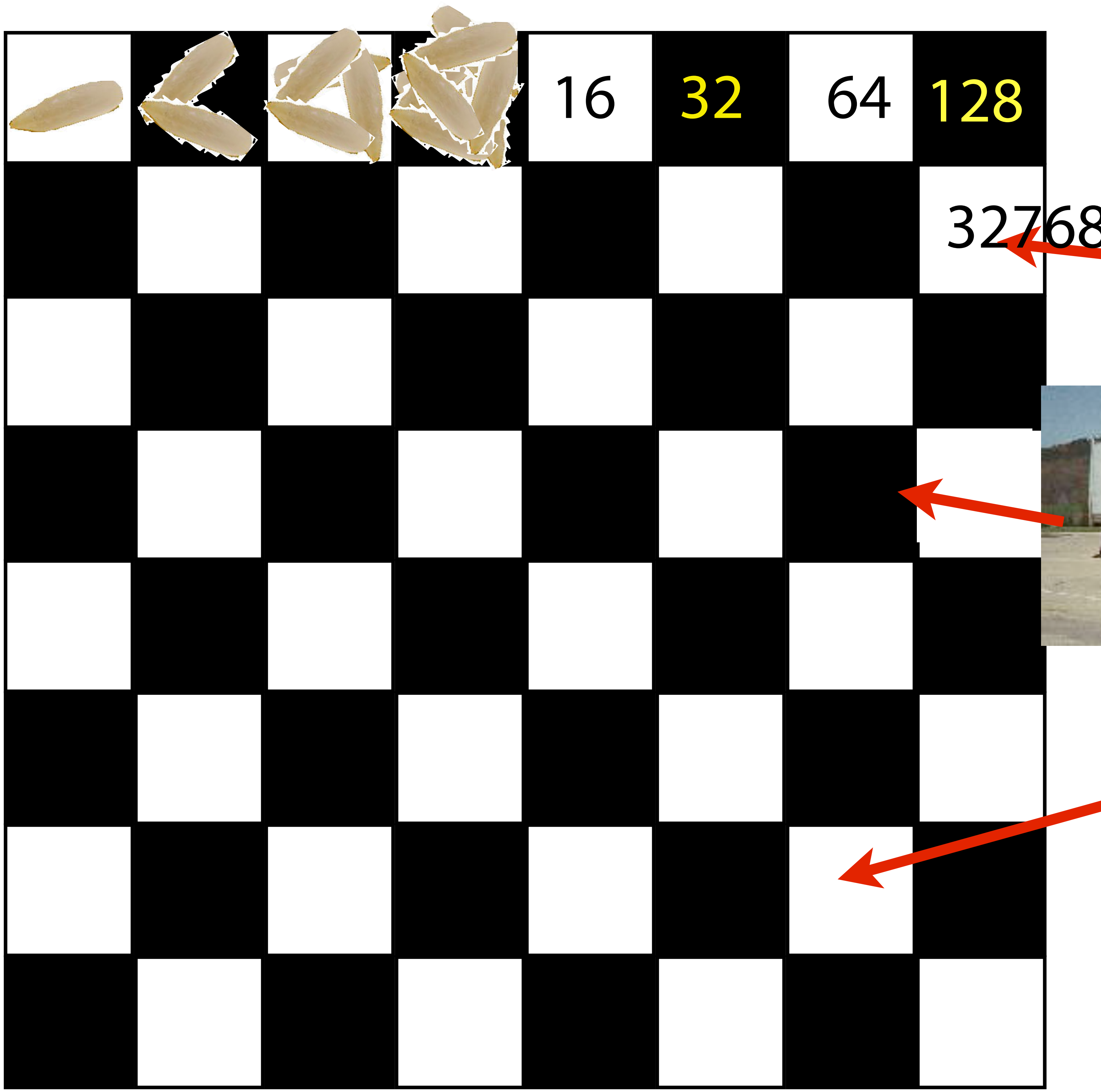
Exponential Growth

Sissa ibn Dahir invents chess
~ 300 b.c.

Sultan Shihram grants
him a wish

1 grain of rice on field 1
2 on field 2
4 on field 3
…

Exponential Growth



world rice
production per year
500 Mio t

Computational Complexity

Prime factors of 16637 = $\boxed{127} \times \boxed{131}$

The computational effort increases with the number of digits.

Factoring on classical computer $e^{c\ell^{1/3}\log(\ell)^{2/3}}$ ℓ = # digits

quantum computer $\ell^2 \log(\ell) \log(\log(\ell))$

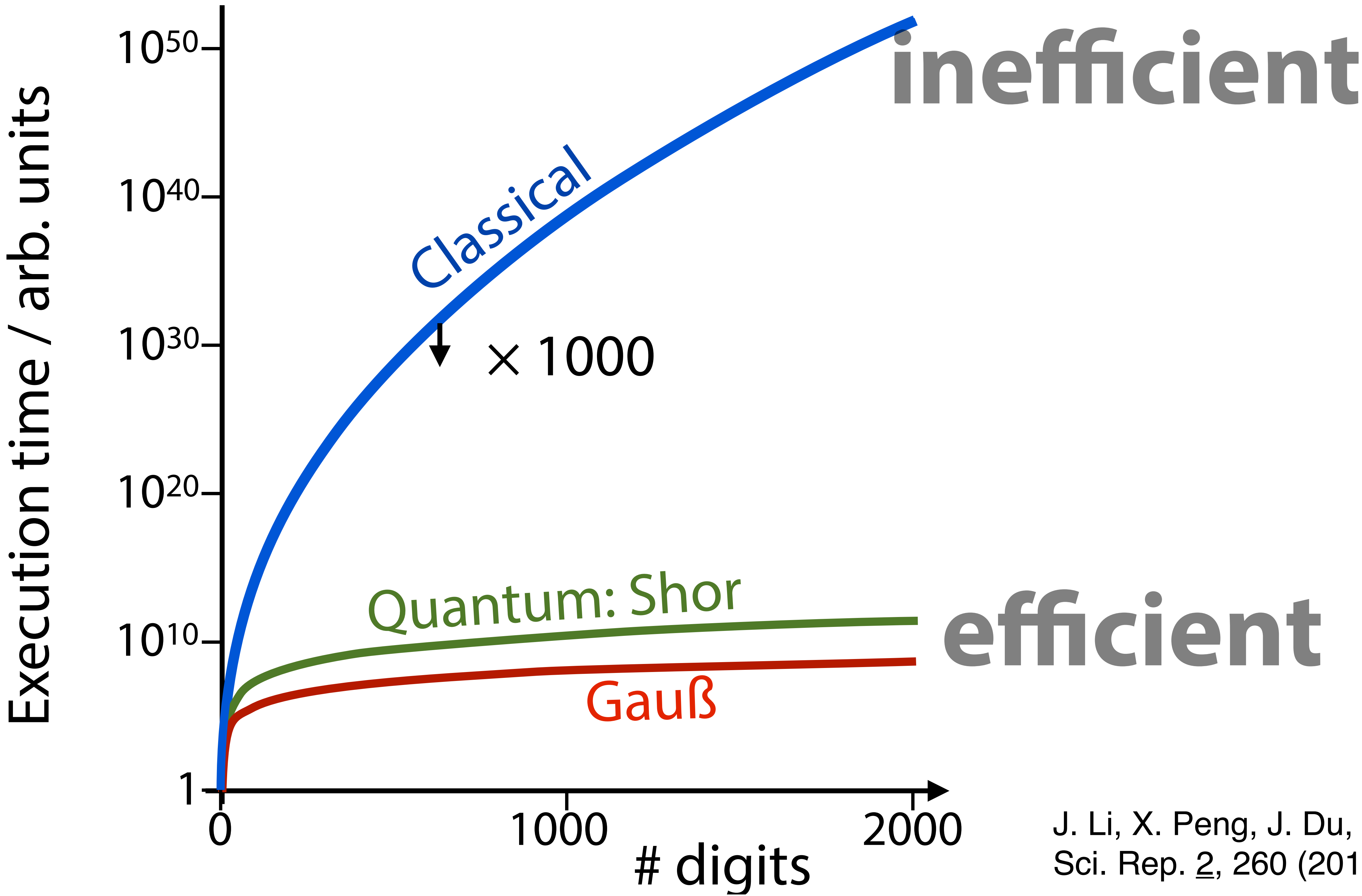
Church-Turing thesis:
Qualitatively identical on all possible computers

Example

ℓ	50	500	2000
classical	1 s	553 days	16 Mio years
quantum	1 hour	9 days	6 months

Why Quantum Computers ?

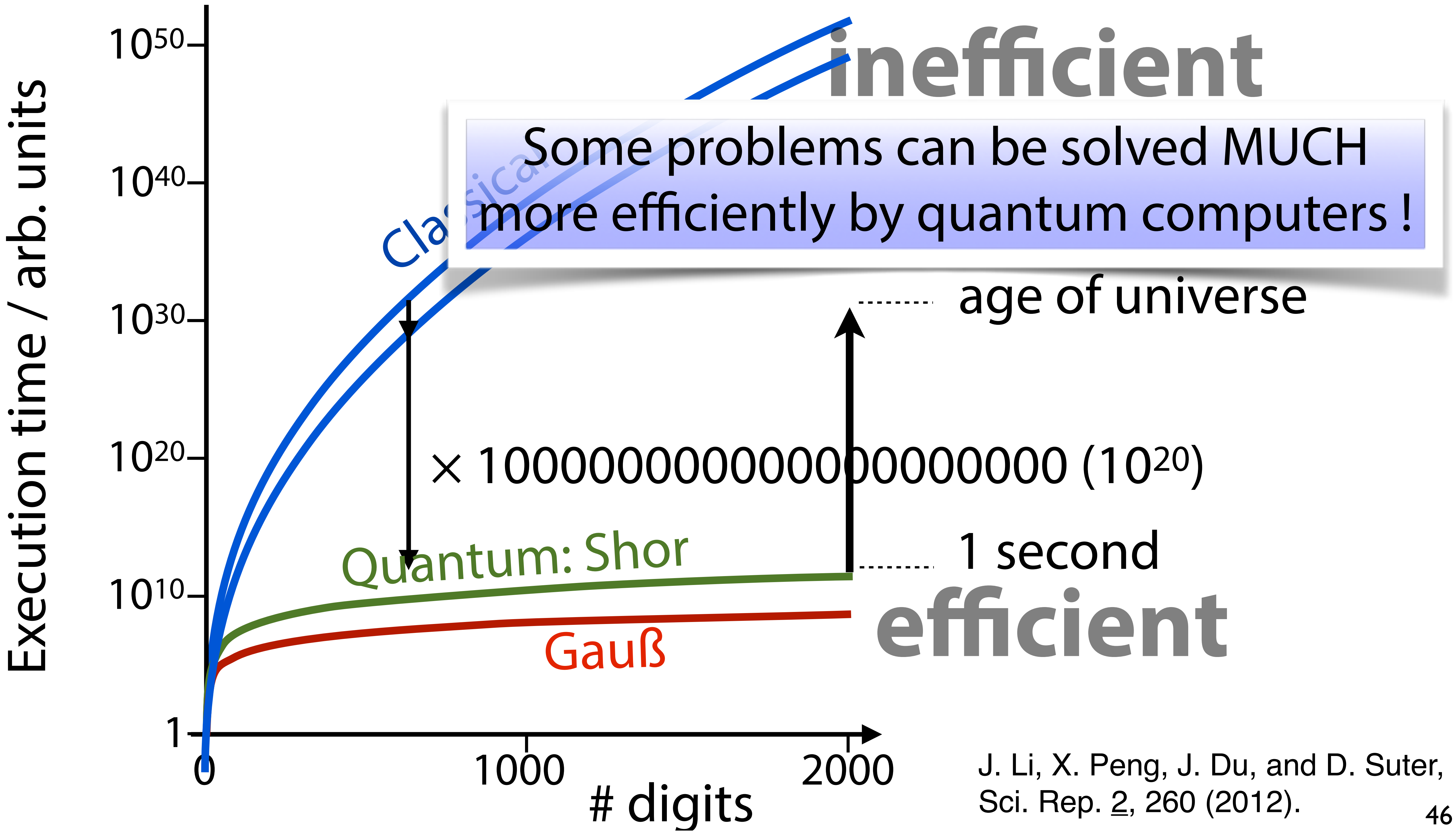
Example of a classically hard problem: find the square-free part of a number, e.g. $175 = 7 \cdot 5^2$



J. Li, X. Peng, J. Du, and D. Suter, Sci. Rep. 2, 260 (2012).

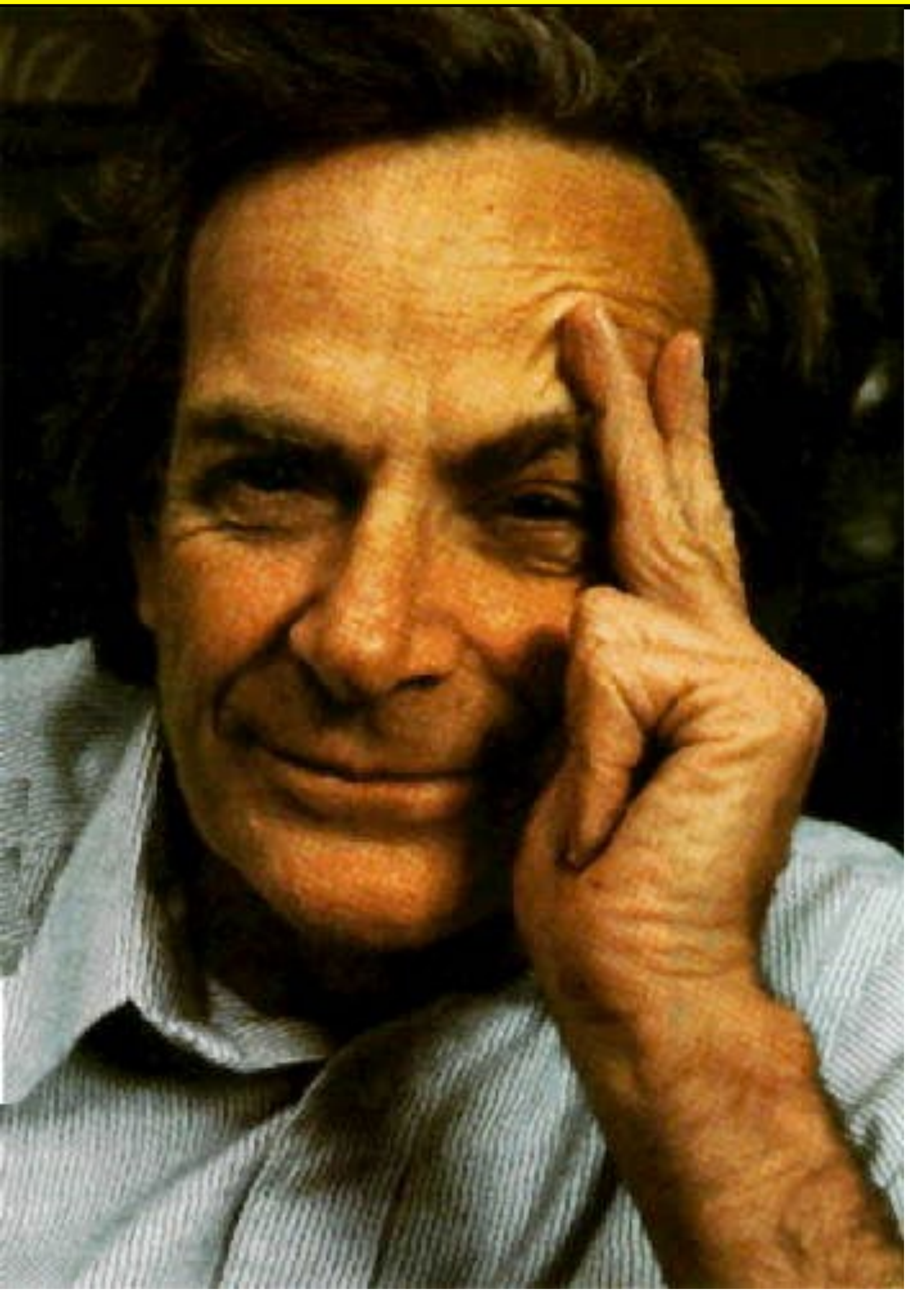
Why Quantum Computers ?

Example: find the square-free part of a number, e.g. $175 = 7 \cdot 5^2$



J. Li, X. Peng, J. Du, and D. Suter, Sci. Rep. 2, 260 (2012).

Simulating Quantum Systems



Another problem

1982 Richard Feynman

R.P. Feynman, *'Simulating physics with computers'*, Int. J. Theor. Phys. 21, 467-488 (1982).

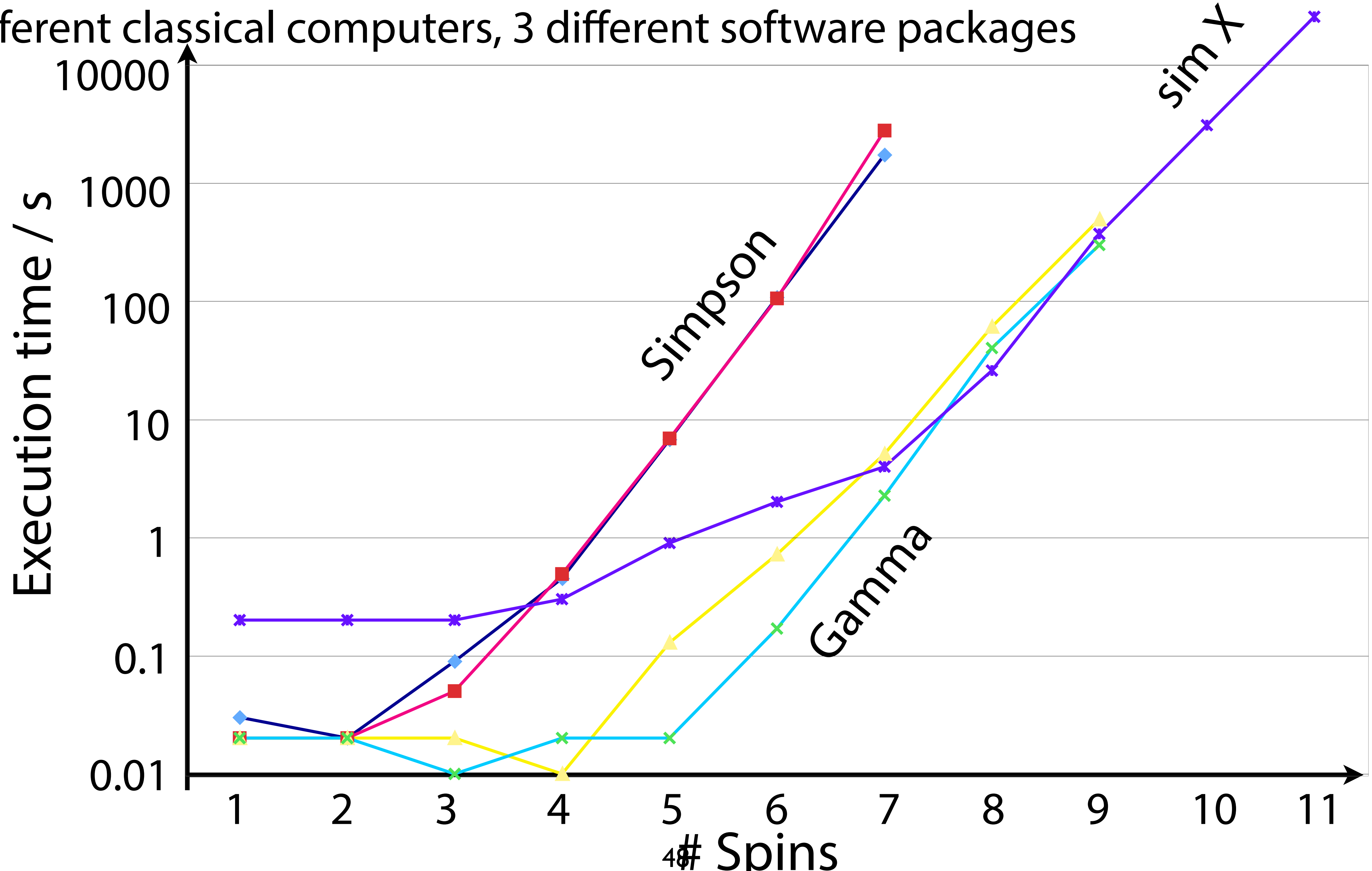
The computational power required to simulate quantum systems grows exponentially with the size of the system.

Scaling of Simulation Times

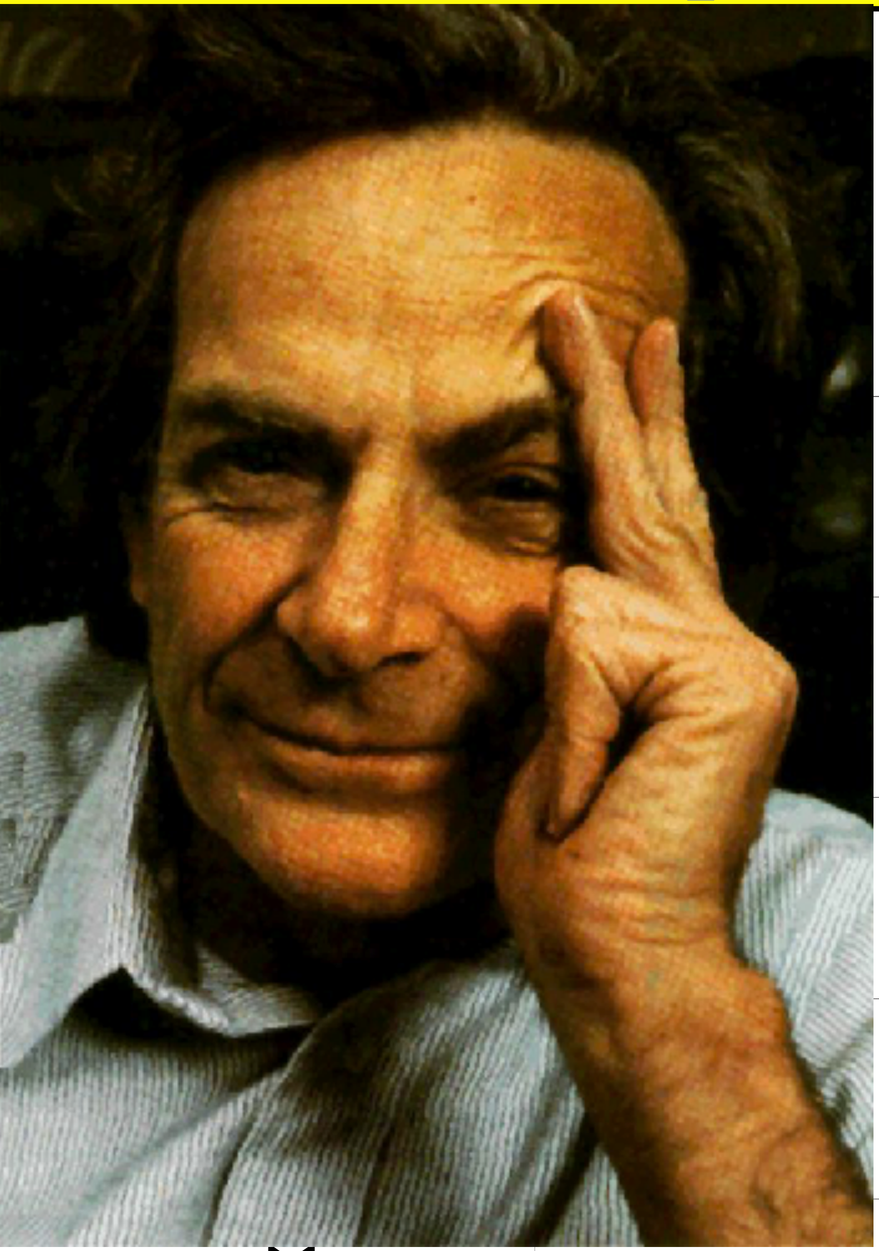
Example: Spin systems

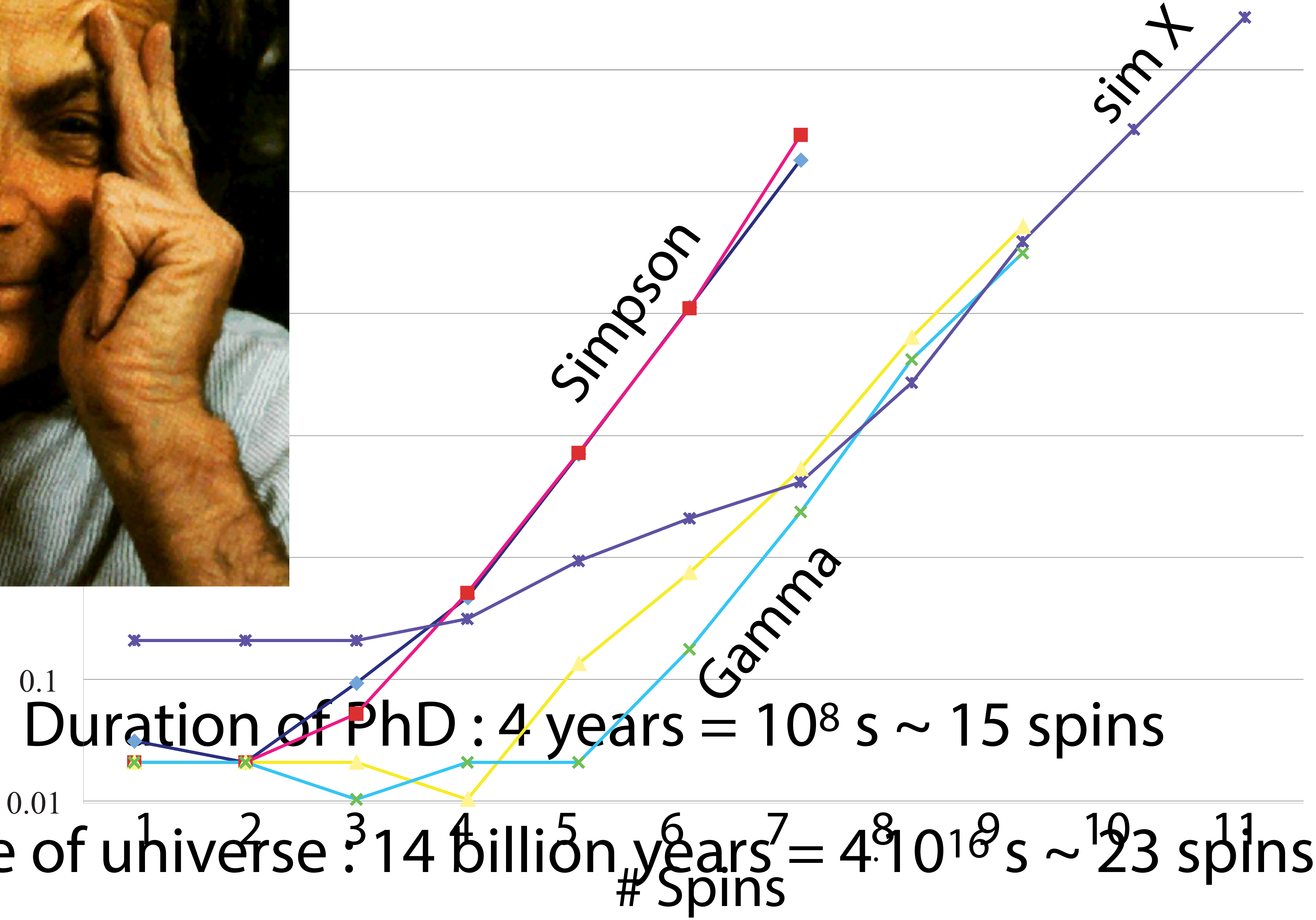
2 unitary operations

3 different classical computers, 3 different software packages



Exponential Scaling

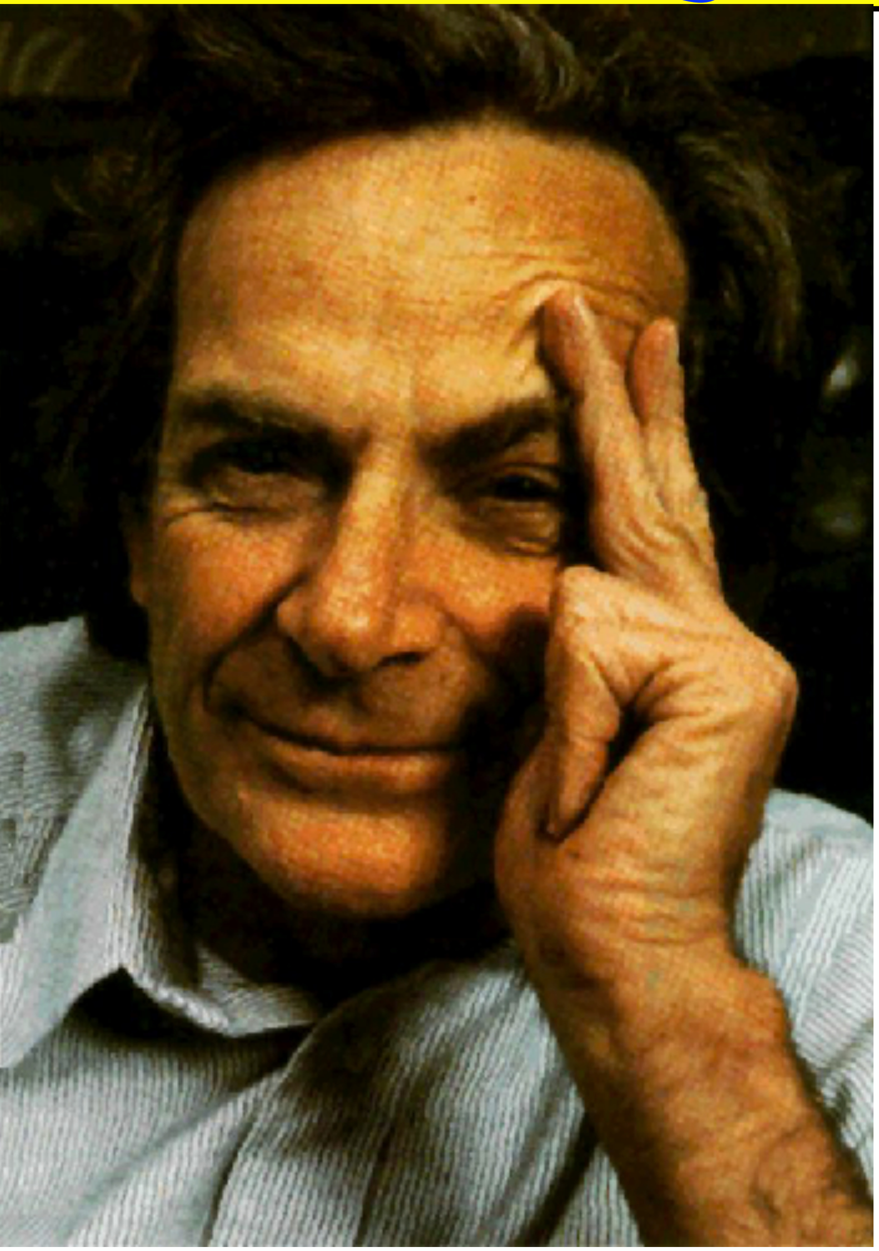


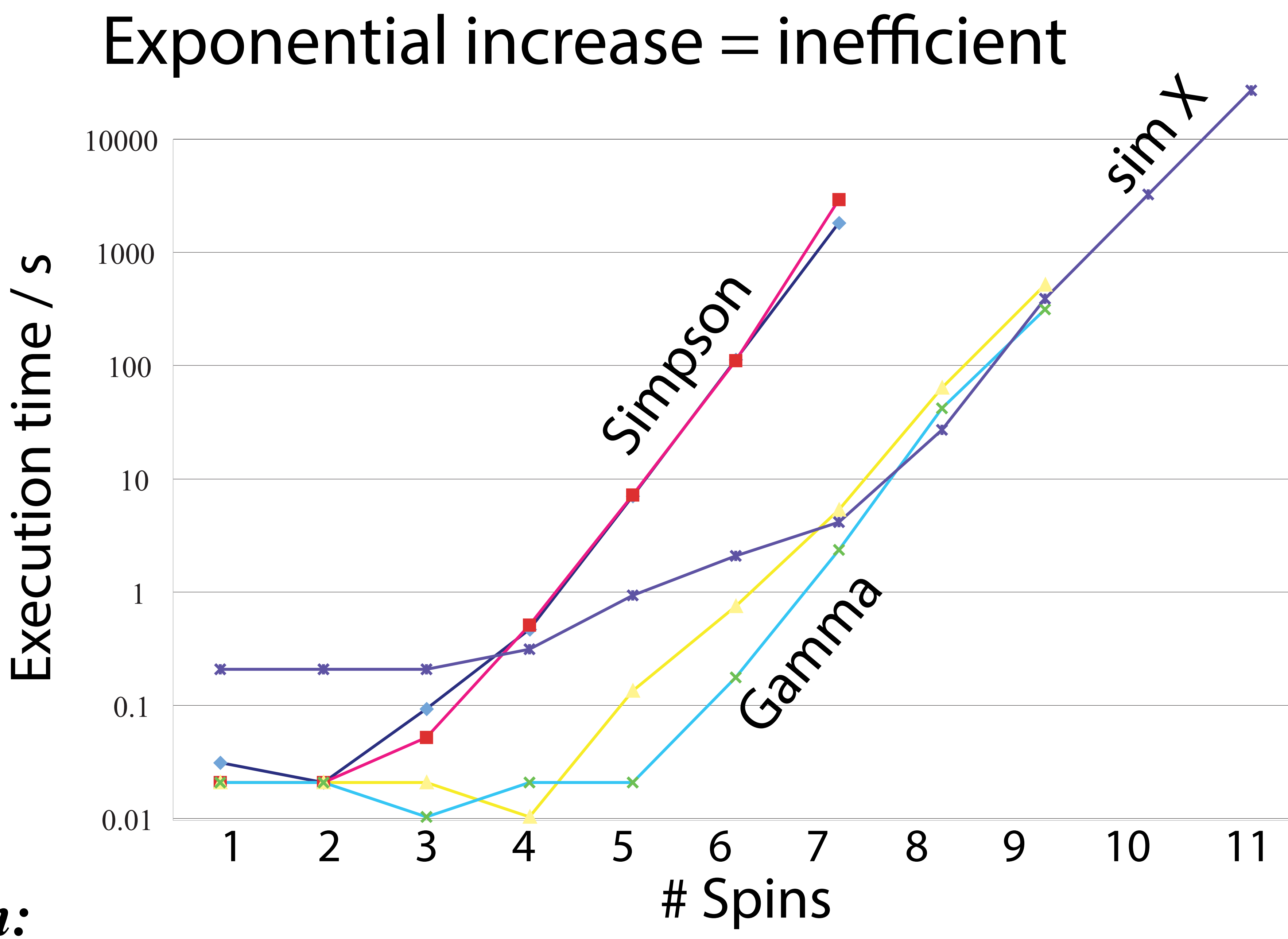


Duration of PhD : 4 years = 10^8 s ~ 15 spins

Age of universe : 14 billion years = $4 \cdot 10^{16}$ s ~ 23 spins

Feynman's Solution

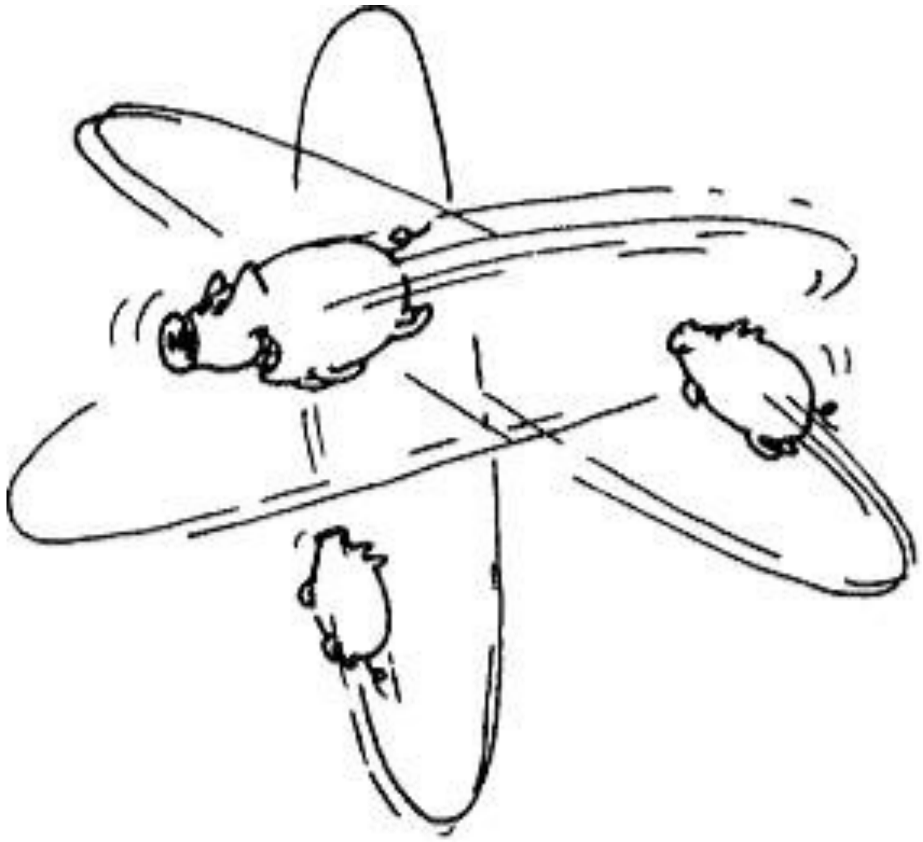




Feynman's proposed solution:

A computer is required that is itself a quantum mechanical system

History of QIP



1982 Benioff:

Quantum computers are universal

1993 Bernstein, Vazirani and Yao:

Quantum systems are more powerful than classical computers

1994 Coppersmith, Shor:

Quantum Fourier transform, factorization

1997 Gershenfeld, Chuang, Cory, Fahmy, Havel:

NMR Quantum computer

Future Computers ?

It wouldn't operate on anything so mundane as physical laws. It would employ quantum mechanics, ..

COVER STORY

Beyond the PC: Atomic QC

Quantum computers could be a billion times faster than Pentium III

By Kevin Maney
USA TODAY

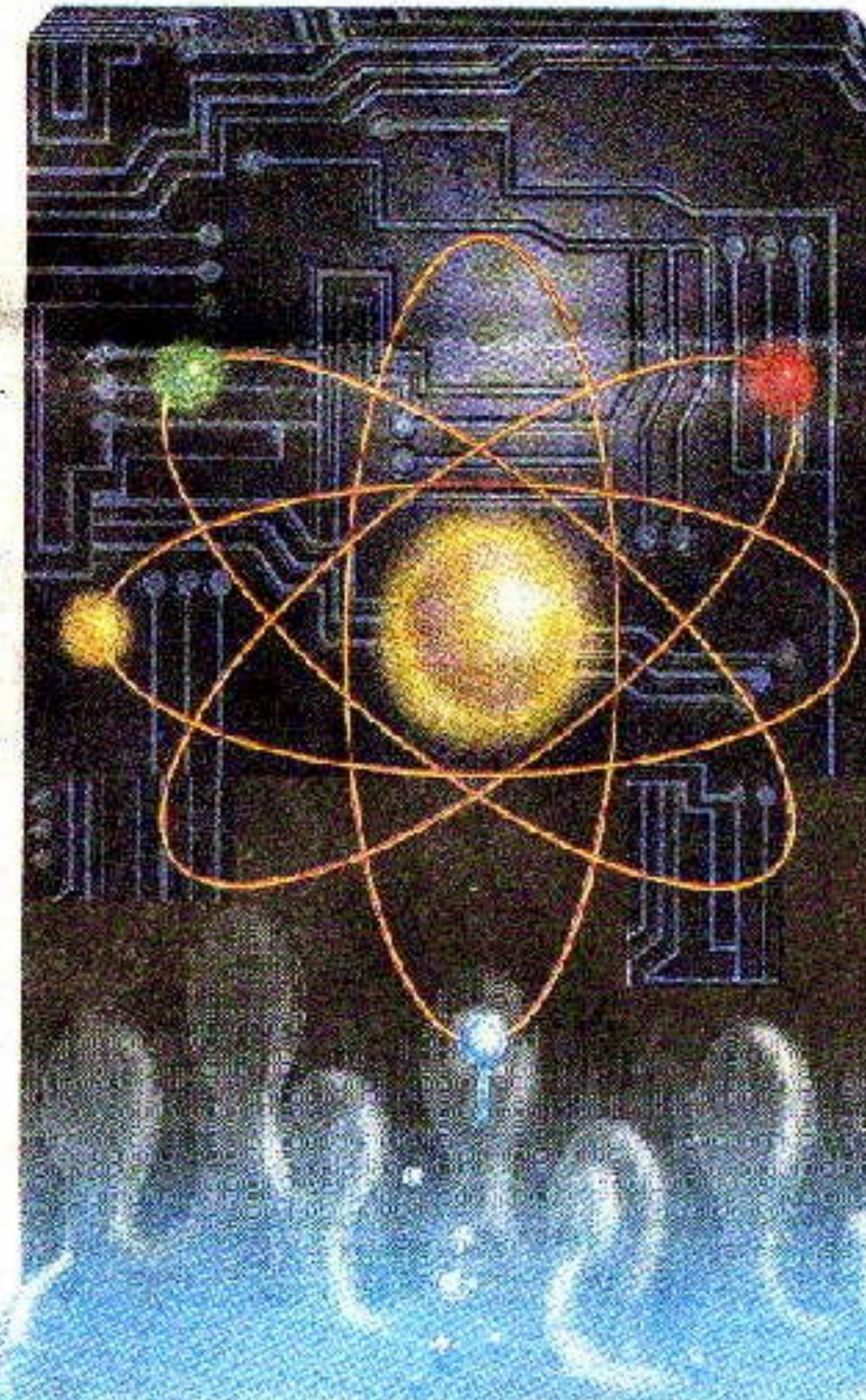
Around 2030 or so, the computer on your desk might be filled with liquid instead of transistors and chips. It would be a quantum computer. It wouldn't operate on anything so mundane as physical laws. It would employ quantum mechanics, which quickly gets into things such as teleportation and alternate universes and is, by all accounts, the weirdest stuff known to man.

This quantum computer would be a data rocket. It probably would do calculations a good 1 billion times faster than a Pentium III PC. It would be able to search the entire Internet — imagine how much will be on the Net in 2030 — in a blink, and could break any cryptographic security code ever invented, no doubt making the CIA very, very nervous.

Sound like science fiction? It's not. Over the past year, quantum computers have become a serious contender for What Comes Next — after Moore's Law takes the current architecture of transistors mounted on microprocessors as far as it can go in increasing processing power.

Quantum computers do calculations using atoms instead of computer chips. The first quantum computers are still rough, expensive one-shot science experiments. But since last year they have been built and have shown that the science works. Labs at places like the Massachusetts Institute of Technology and Oxford University are pumping up quantum computer projects. Companies such as IBM and Hewlett-Packard are leaping in. The federal government, which is both worried about and intrigued by quantum computing, has set up one of the most well-funded quantum computing labs at Los Alamos National Laboratory.

"This area has gone off like a big bang. It's breathtaking," says Stan Williams, head of Hewlett-Packard's labs. "The potential is so huge and it would be so disruptive, it could completely change the



Digital Information

"Hello" = 72, 101, 108, 108, 111 = 01001000 01100001 01101100

1Bit

Physical representation

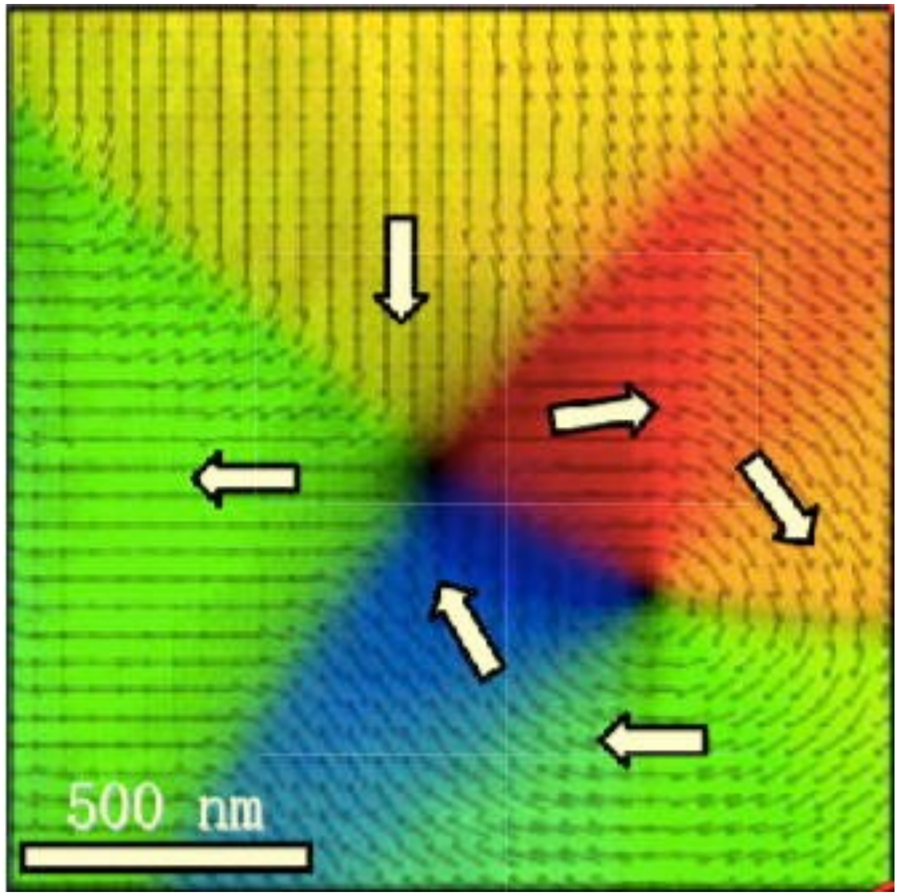
logical value

Voltage

Magnetization

1

0



Quantum Mechanics and Computing

Classical electronics ~ semiconductor electronics

Quantum mechanics is the foundation of solid state physics:

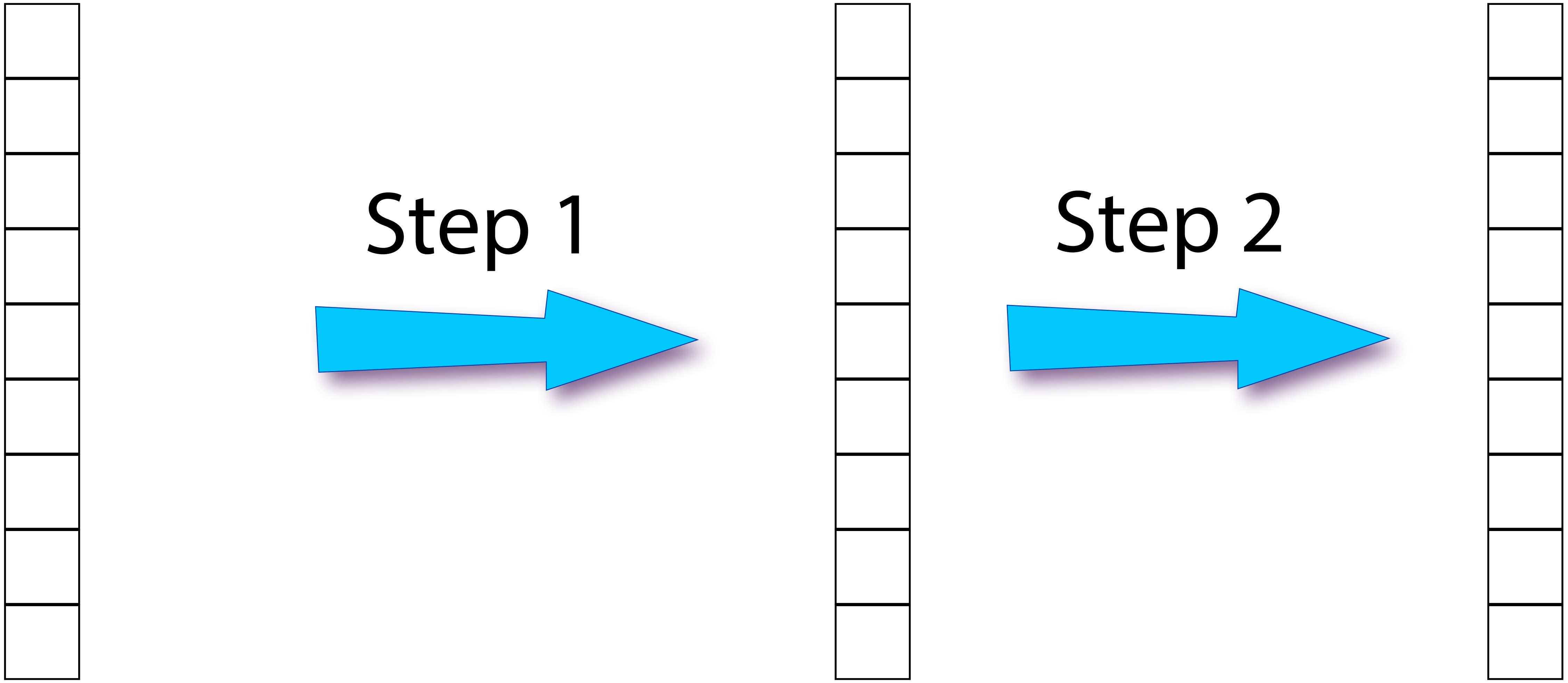
- band structure
- semiconductors vs. metals
- resistivity
- thermal properties
- etc.

Engineers do not need to know quantum mechanics:
all these effects can be summarized in terms of material parameters (I/V curves, conductivities etc.)

Today's computers can be described classically

Models of Computation

N-bit register



Classical Processing

Boolean logic

Example 1 : **NOT**

Input Output

$$\left.\begin{matrix}0\\1\end{matrix}\right\} \rightarrow \left\{\begin{matrix}1\\0\end{matrix}\right.$$

Example 2 : **AND**

Input Output

$$\left.\begin{matrix}00\\01\\10\\11\end{matrix}\right\} \rightarrow \left\{\begin{matrix}0\\0\\0\\1\end{matrix}\right.$$

AND gate loses information

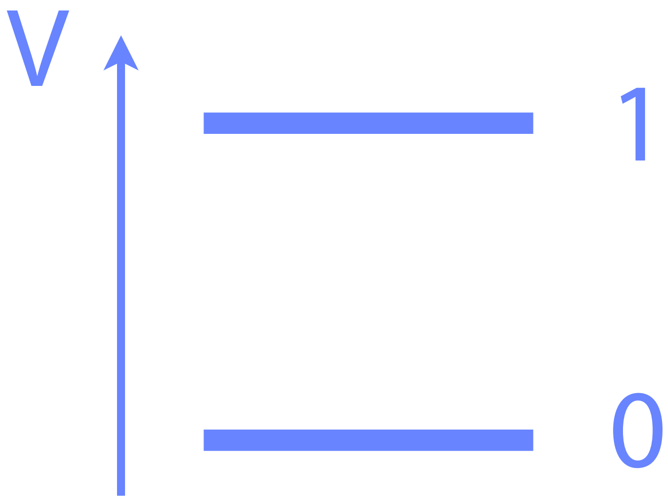
$\downarrow$

Minimal energy dissipation : $k_B T \ln 2$

Digital Information

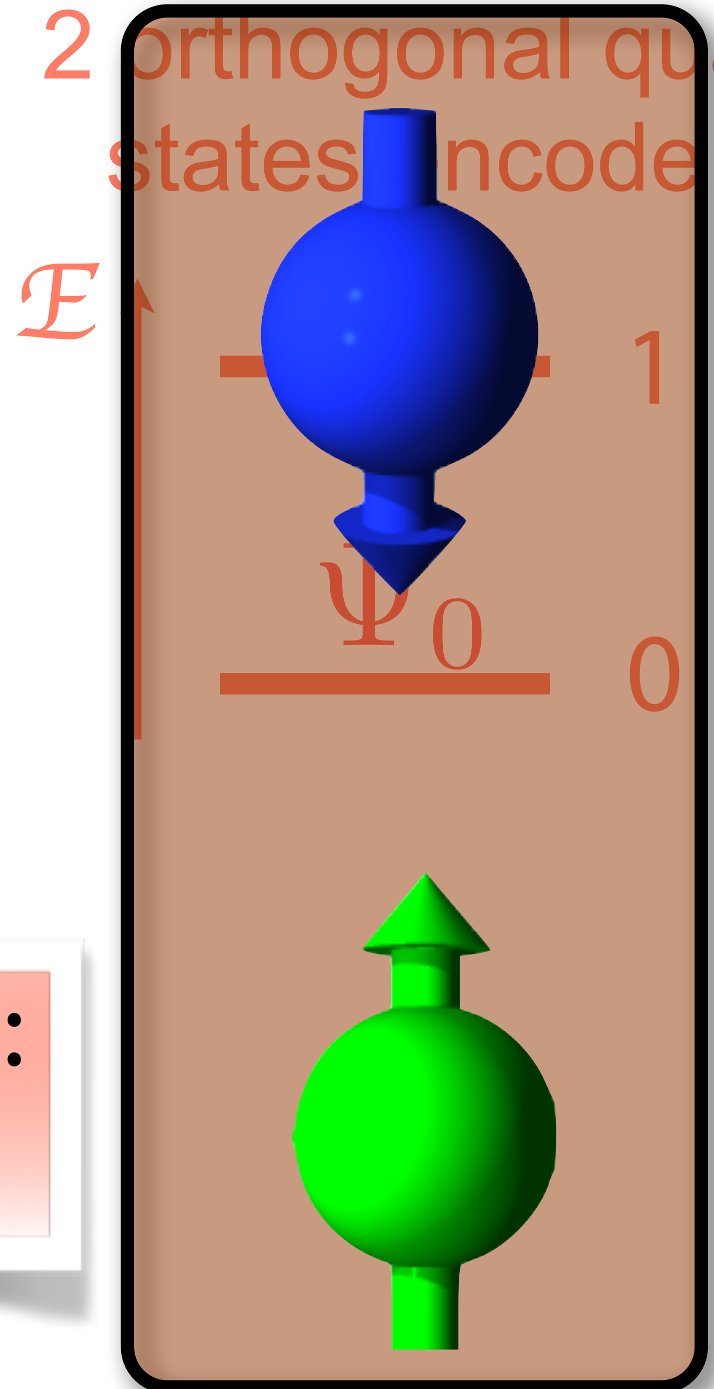
Classical

2 different voltages encode 1 bit



Quantum mechanical

2 orthogonal quantum states encode 1 bit



or

“Qubit”

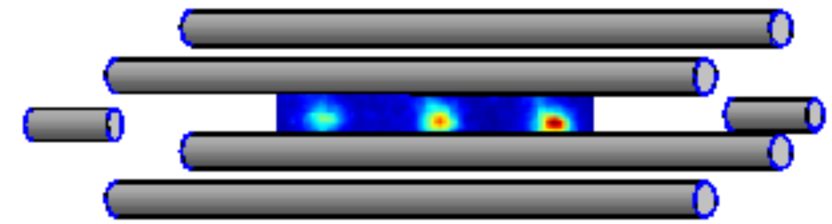
superposition

Natural Qubit:
Spin 1/2

Unitary Transformations

Quantum register

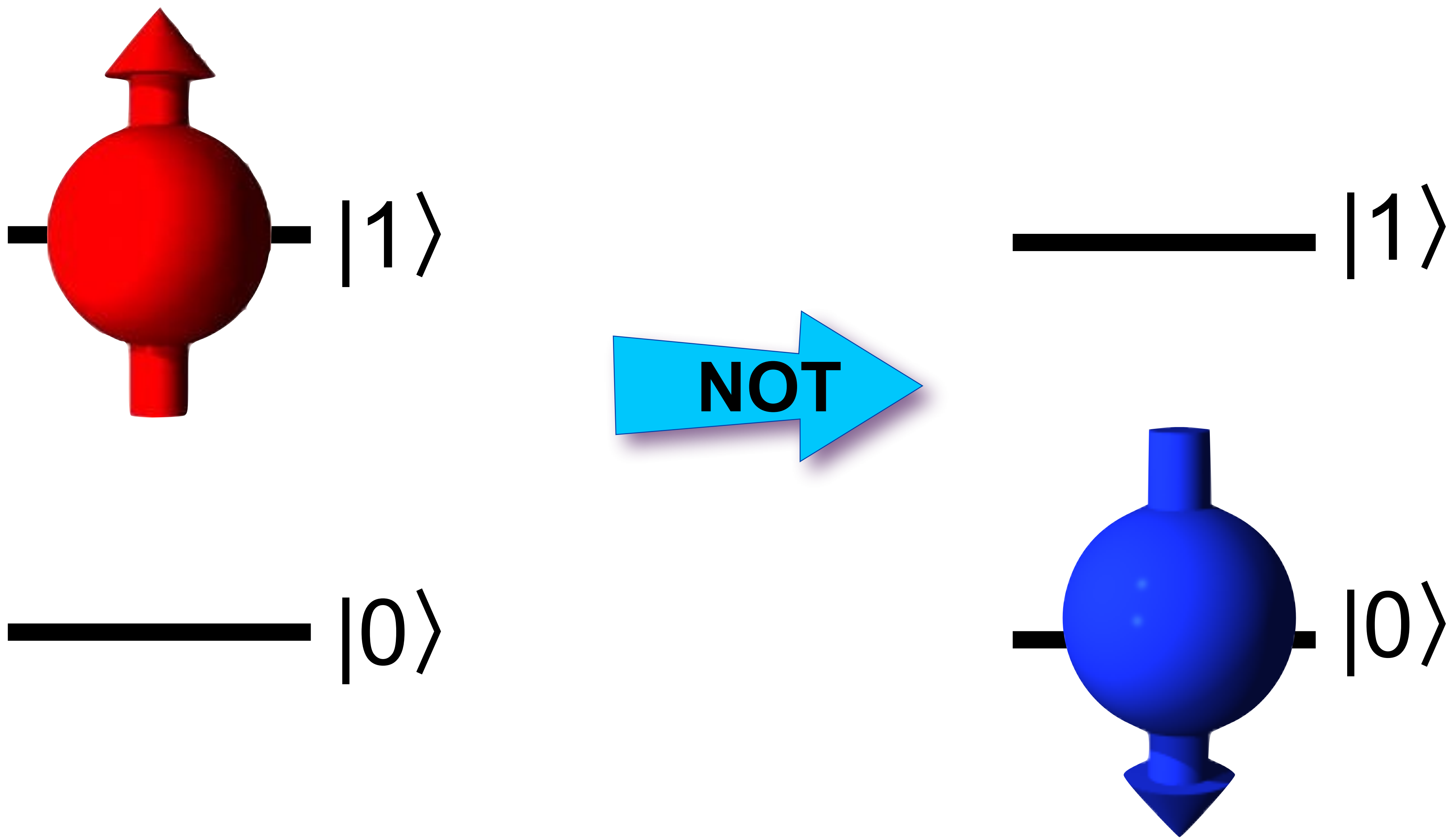
Logical operation $$\Psi_{out} = U\Psi_{in}$$



- Quantum logical operations are reversible
- No dissipation
- Logical operations driven by control fields

Gates for Qubits

1 qubit, e.g. NOT



2 Qubit Gates

e.g. CNOT

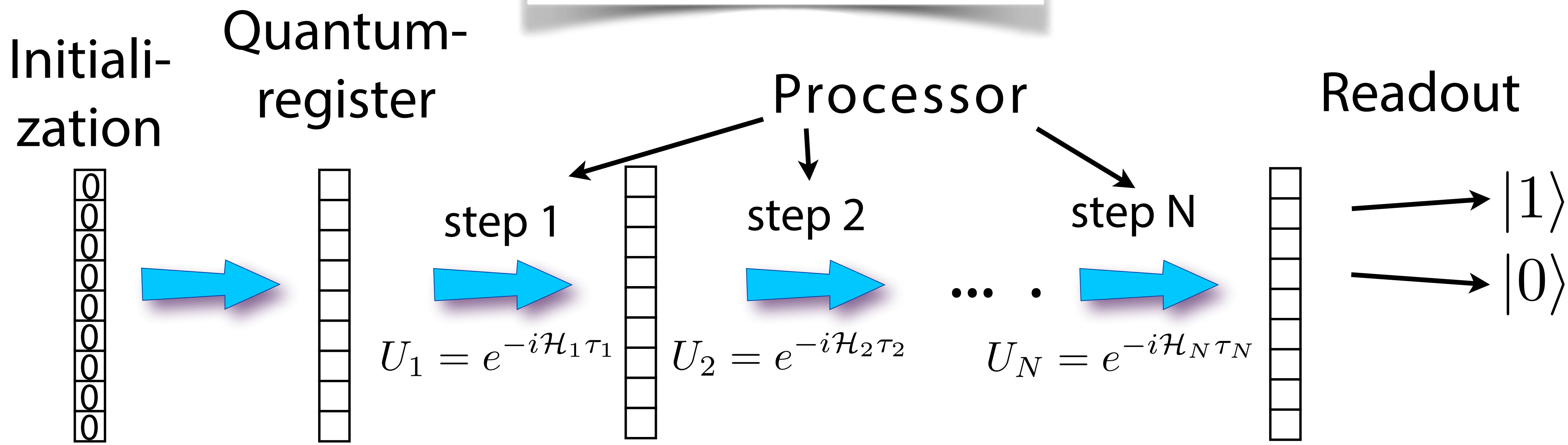
Control qubit Target qubit

$$\left.\begin{array}{c}0\;0\\0\;1\\1\;0\\1\;1\end{array}\right\}\Rightarrow\left\{\begin{array}{c}0\;0\\0\;1\\1\;1\\1\;0\end{array}\right.$$

Target qubit is flipped if control qubit = 1

Basics of Quantum Computing

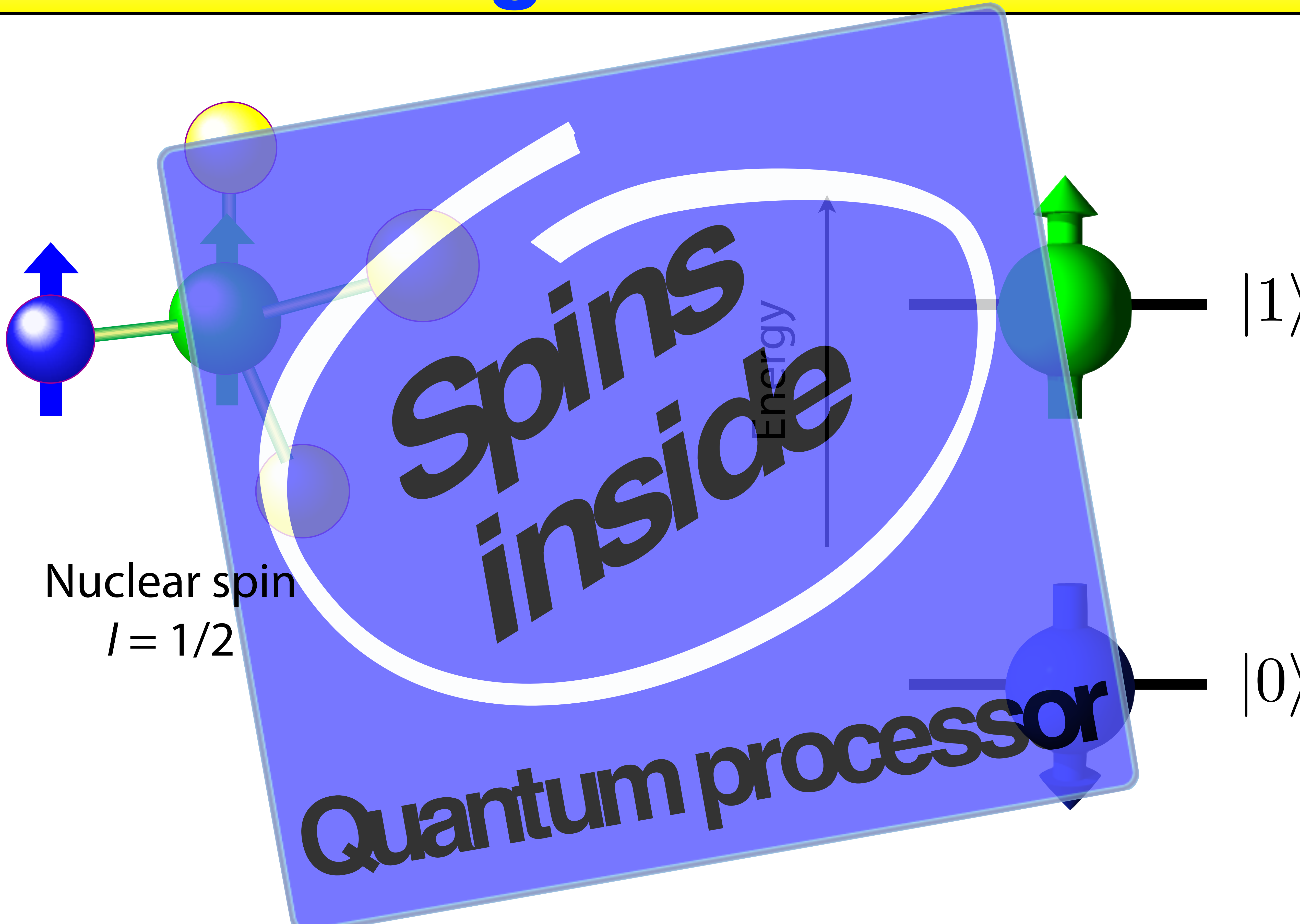
The network model



- The power of the implementation depends on the number of qubits in the quantum register: *N* qubits provide *2^N* computational basis states

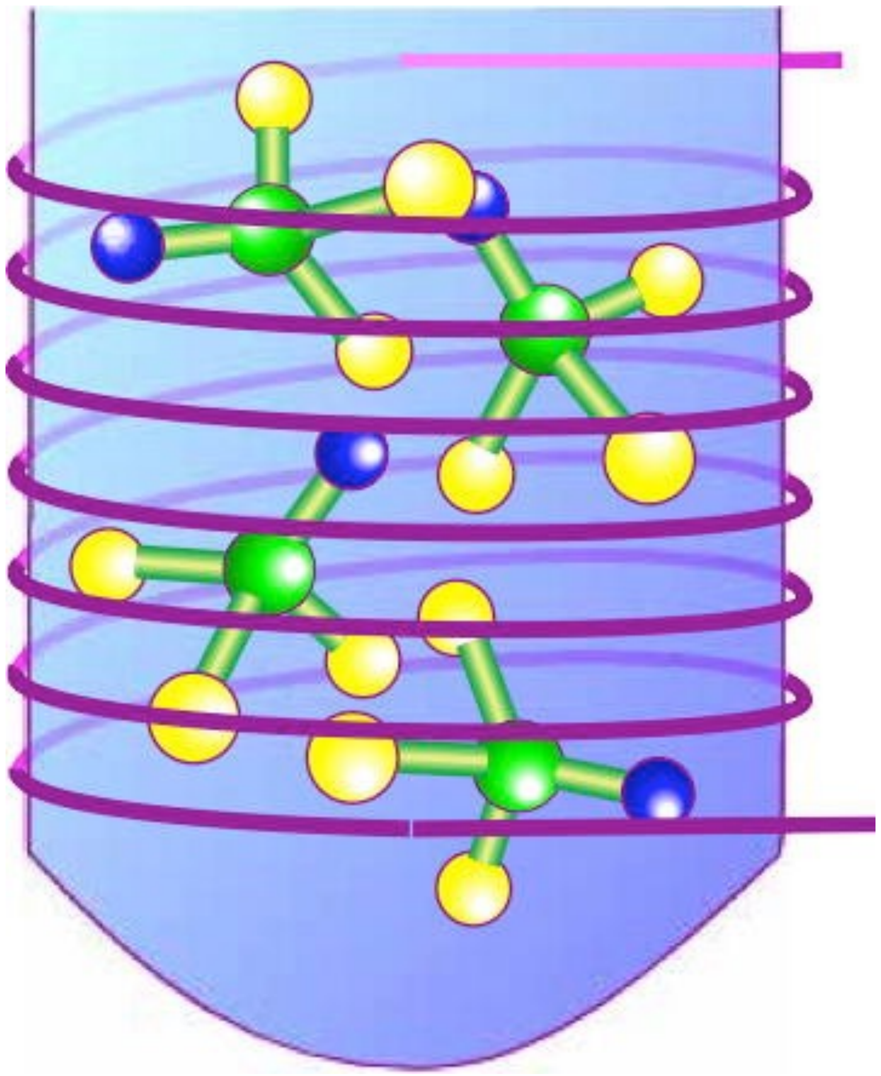
- Logical operations act on superposition states
  → "Quantum parallelism"

Nuclear Magnetic Resonance

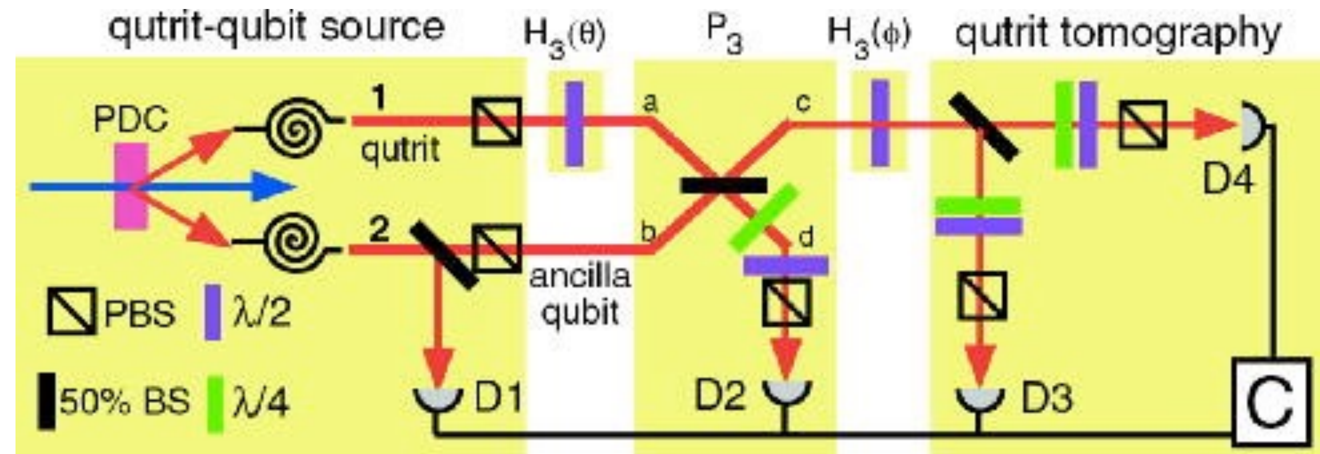


Implementations

- Nuclear Magnetic Resonance (NMR)

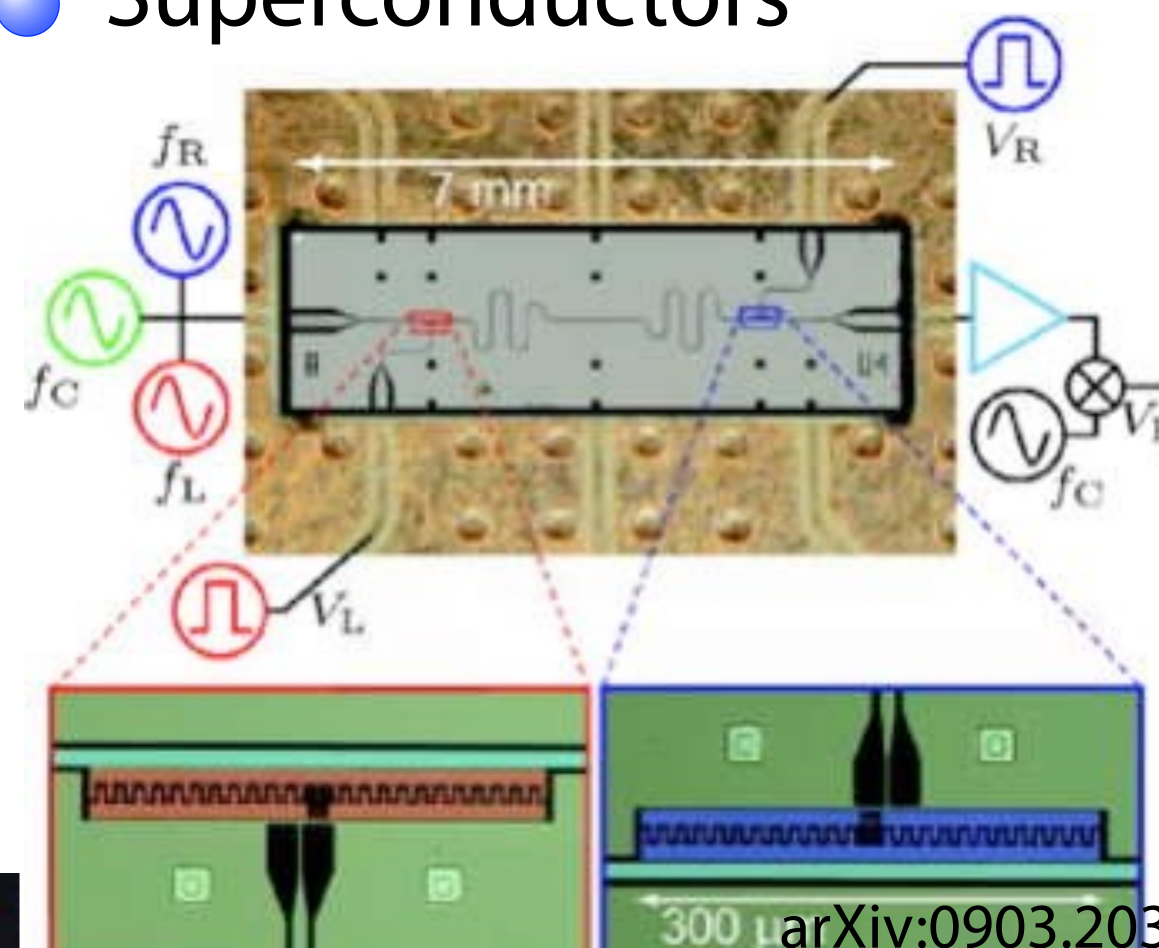


- Photons



PRL 100, 060504 (2008)

- Superconductors



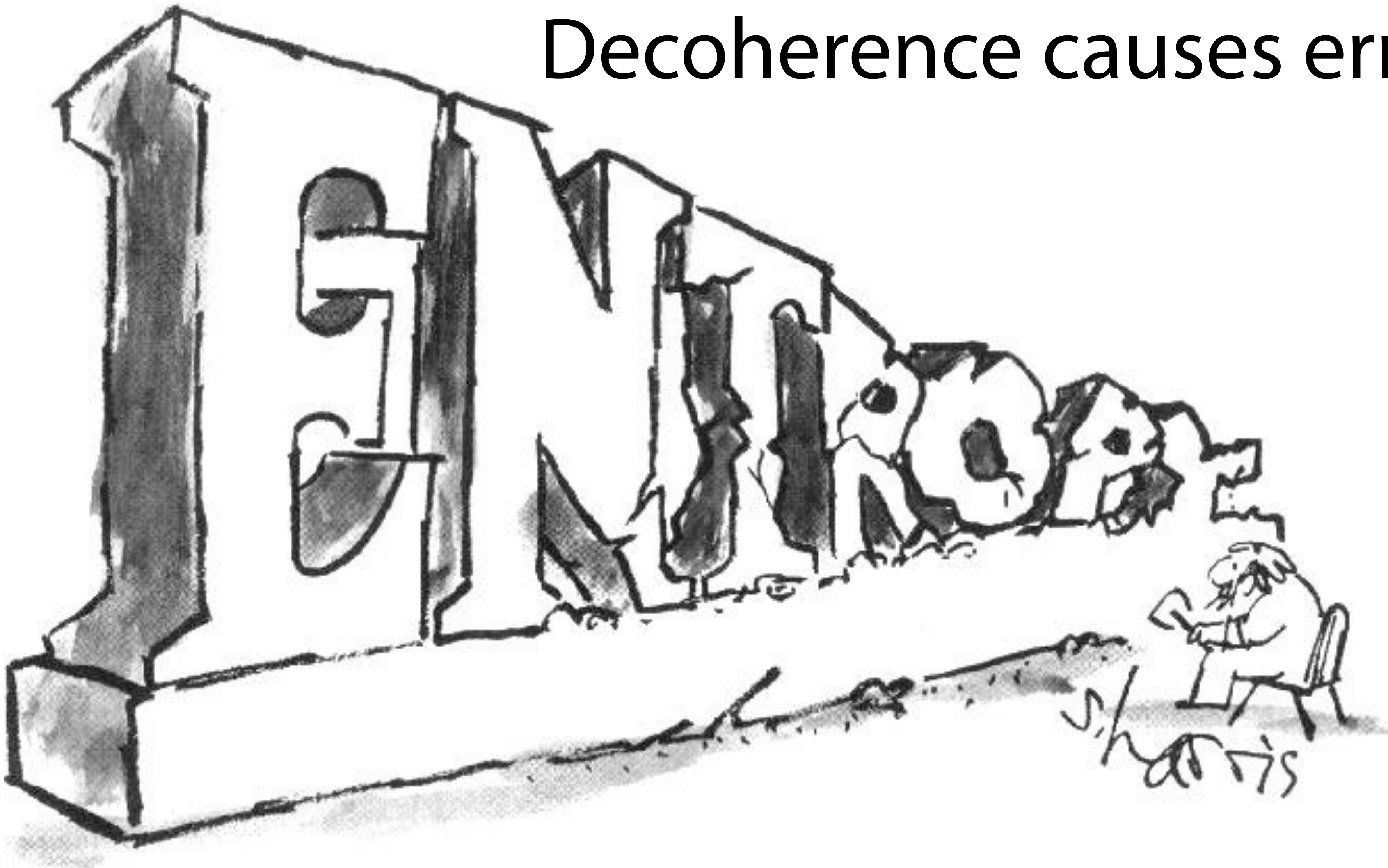
arXiv:0903.2030

- Trapped Ions

... and more, e.g. neutral atoms, defects in solids, quantum dots, elec

Scalability and Decoherence

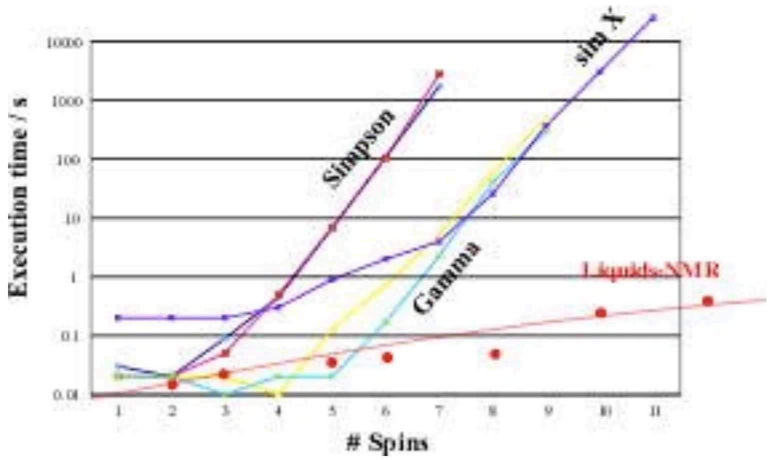
Decoherence causes errors



Main source: coupling to environment

Errors are difficult to correct in quantum computers

Will it Work ?



Will quantum computers replace classical computers?

No !

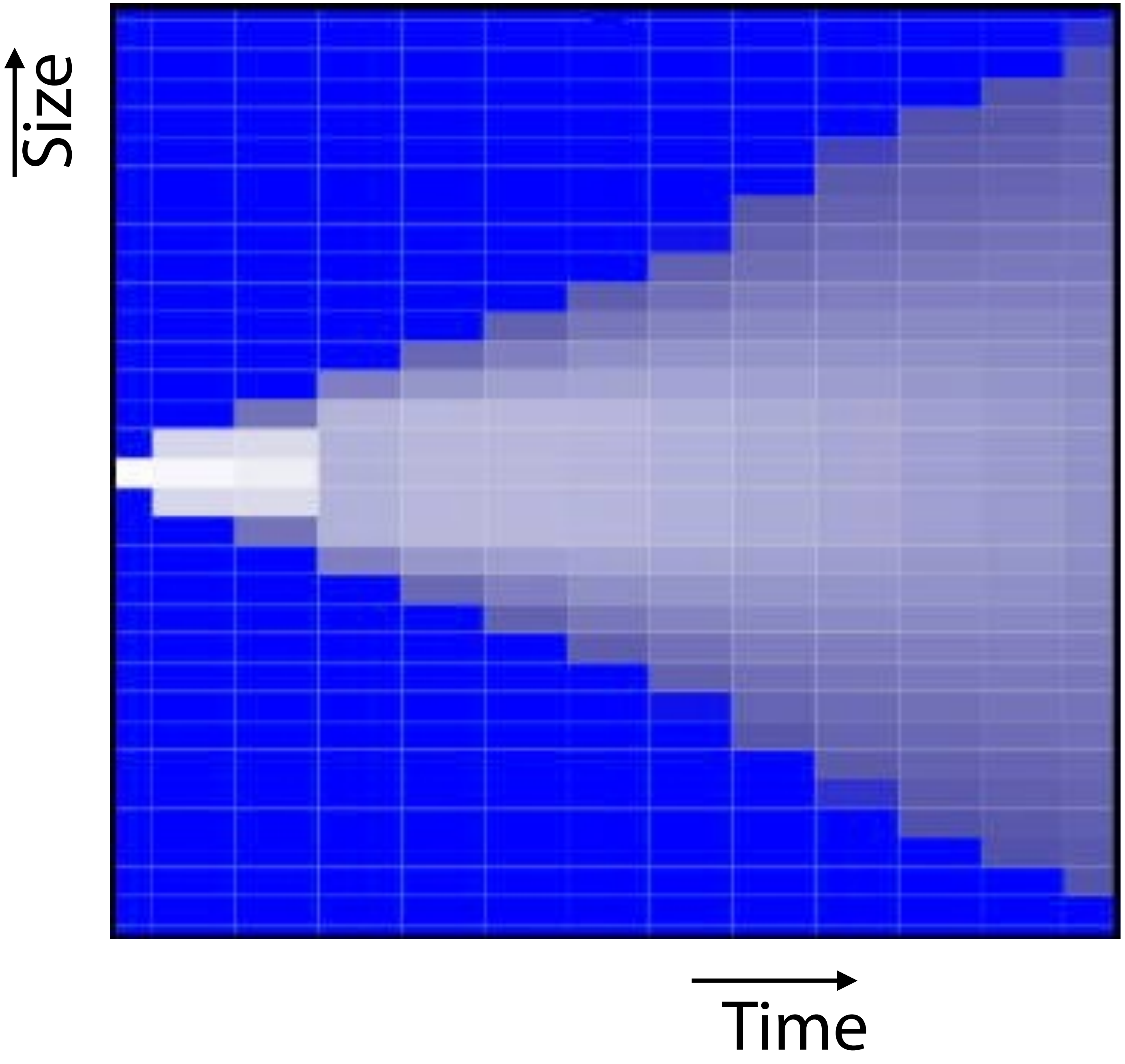
Will quantum computers be useful ?

Yes !

Answer 1: Yes: Quantum computers are useful for quantum simulations.

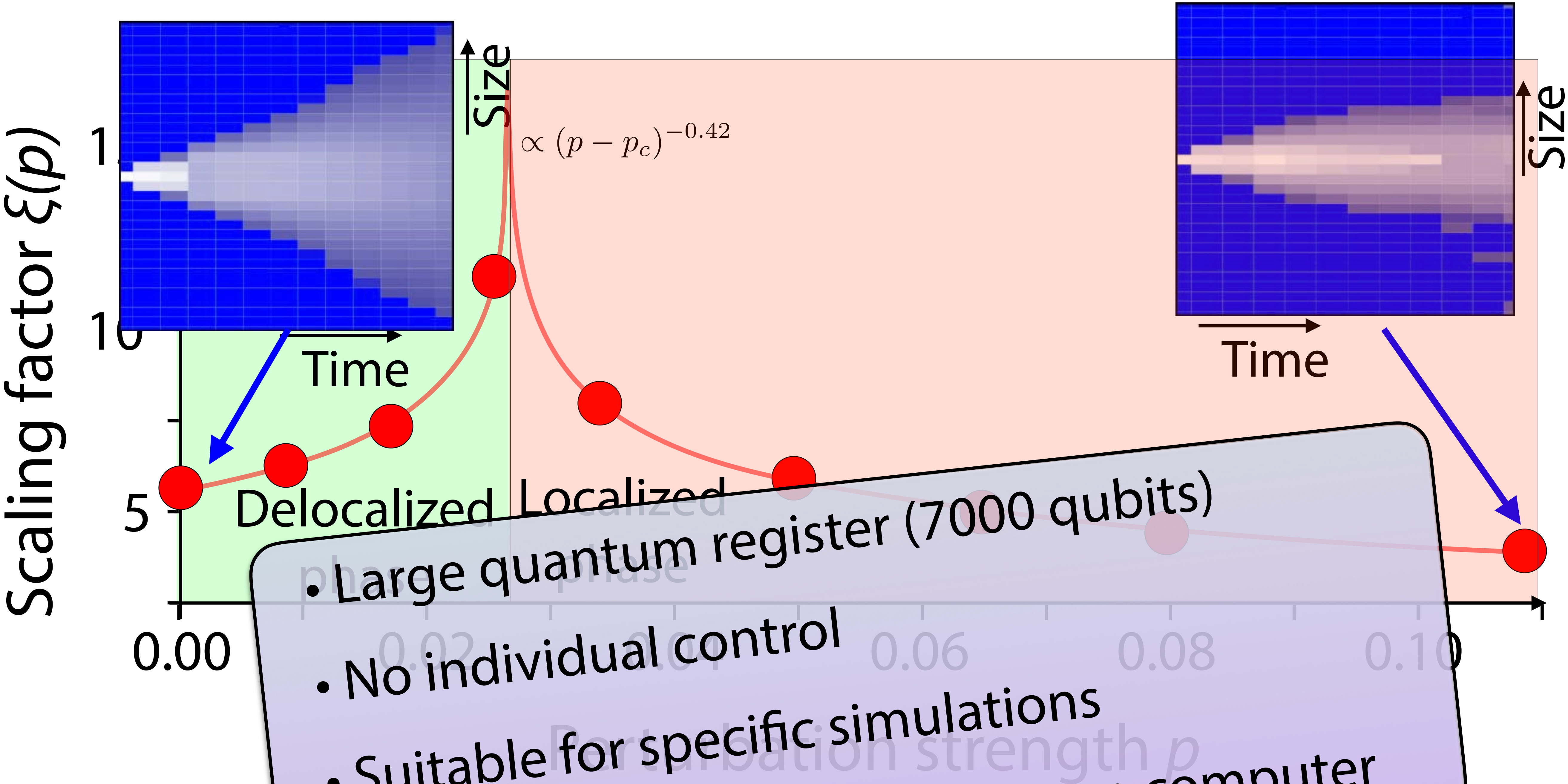
Quantum Simulations : Localization

Physical system: nuclear spins



Quantum Simulations : Localization

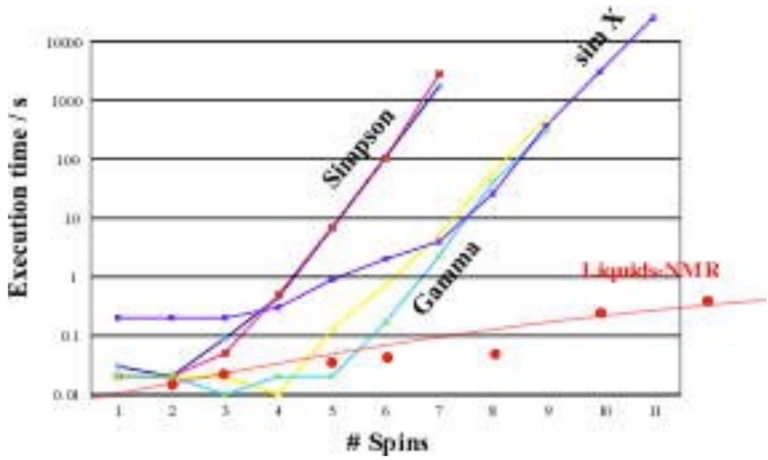
Physical system: nuclear spins



- Large quantum register (7000 qubits)
- No individual control
- Suitable for specific simulations
- **Not** a general purpose quantum computer

Experimental observation of a phase transition in the evolution of many-body systems with dipolar interactions
G. A. Álvarez, D. Suter, R. Kaiser, Science 349, 846 (2015).

Will it Work ?



Will quantum computers replace classical computers?

No !

Will quantum computers be useful ?

Yes !

Answer 1: Yes, they are! Quantum computers are useful for quantum simulations.

Answer 2: Yes, since future computers will use quantum effects.

Answer 3: The most important applications of any sufficiently advanced technology are always created by this technology. (Kroemer,1995: The lemma on new technologies)

Applications ?

Answer 3: The most important applications of any sufficiently advanced technology are always created by this technology. (Kroemer,1995: The lemma on new technologies)

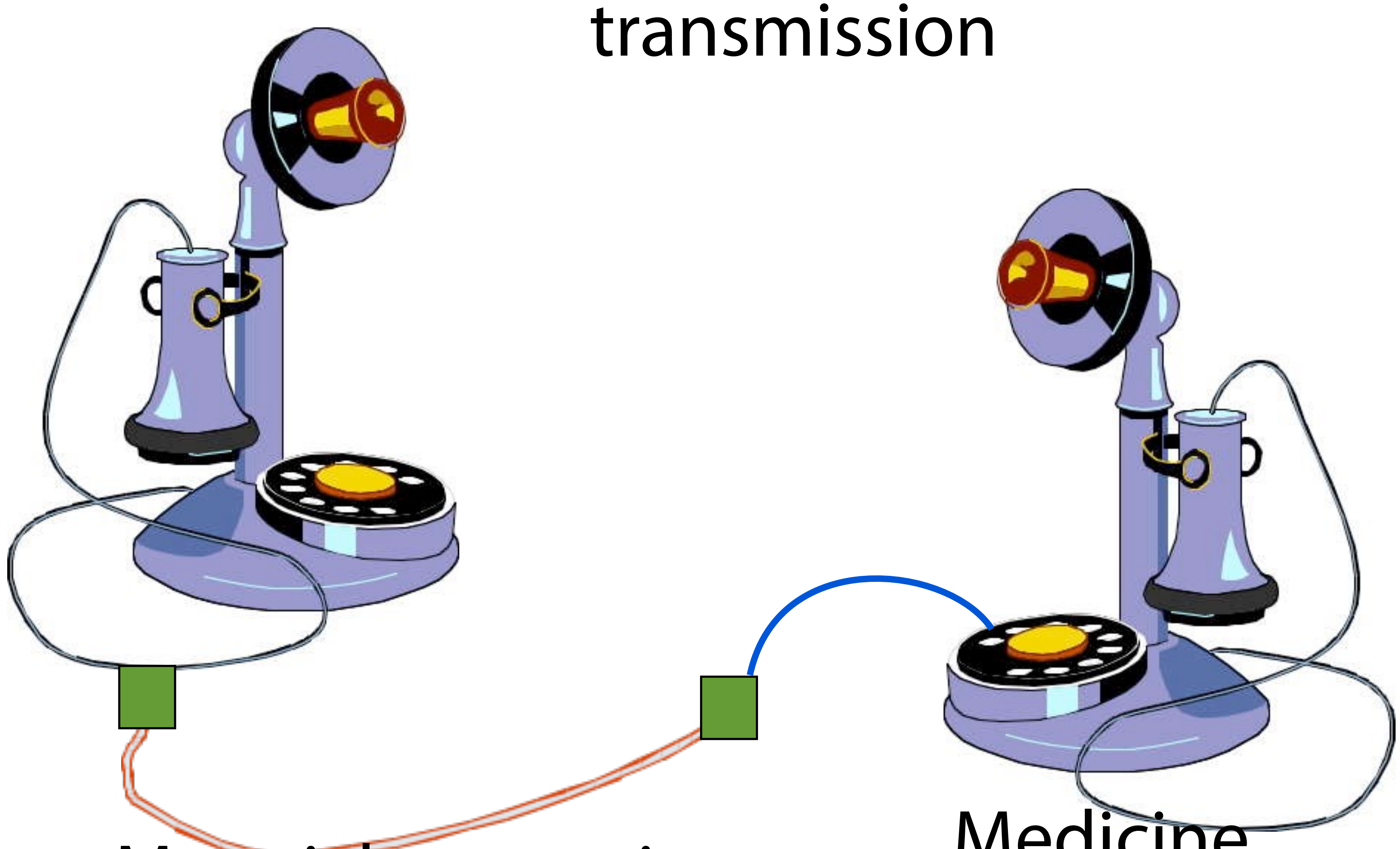
My proposal to develop the double-heterostructure laser was turned down for the following reason:

“This development cannot possibly have any applications”

Herbert Kroemer, Nobel price lecture, RMP 73, 783-793 (2001).

Laser Applications

optical data
transmission

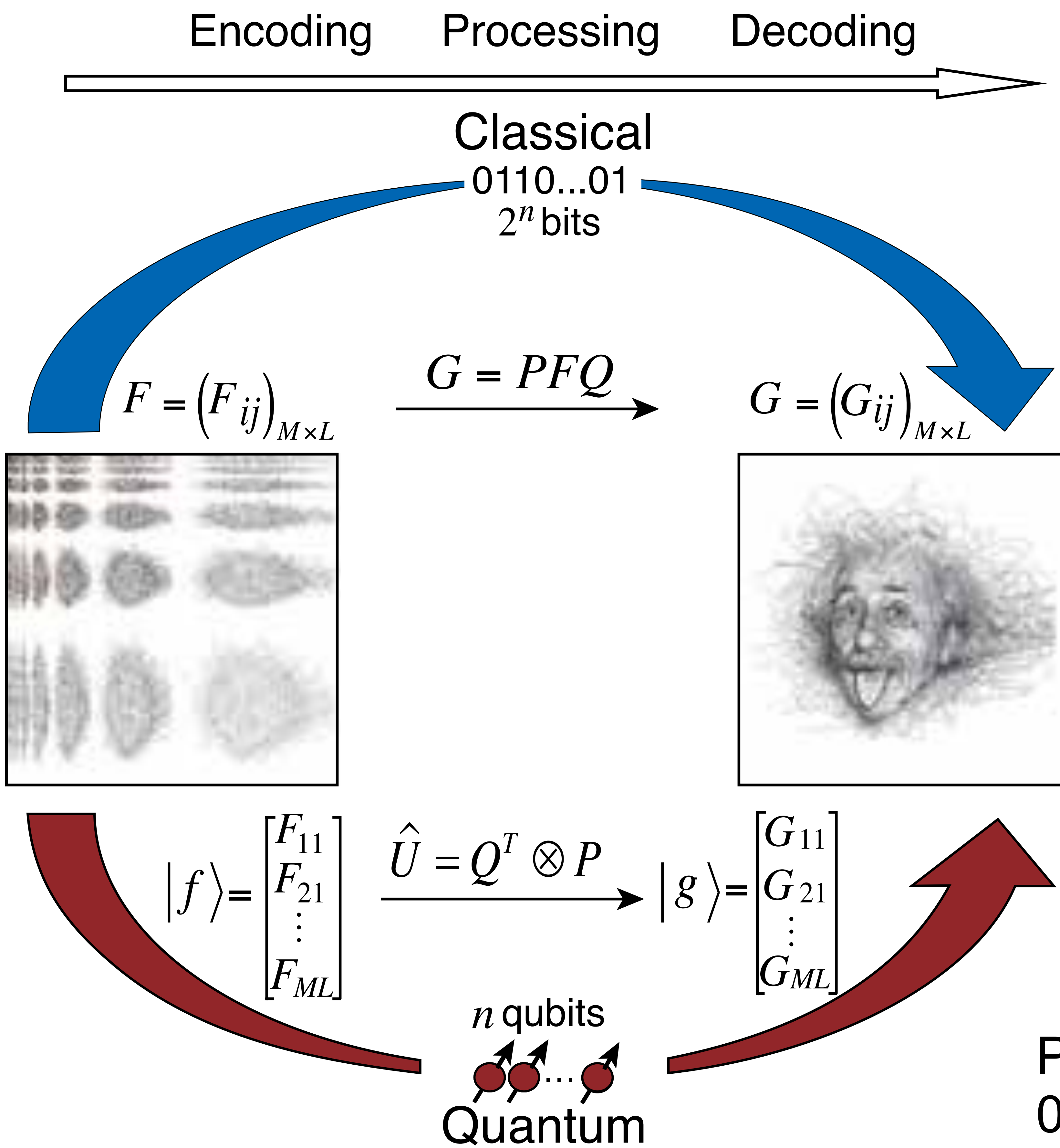


Laserprinter

Material processing
Light shows

Medicine
Measurement

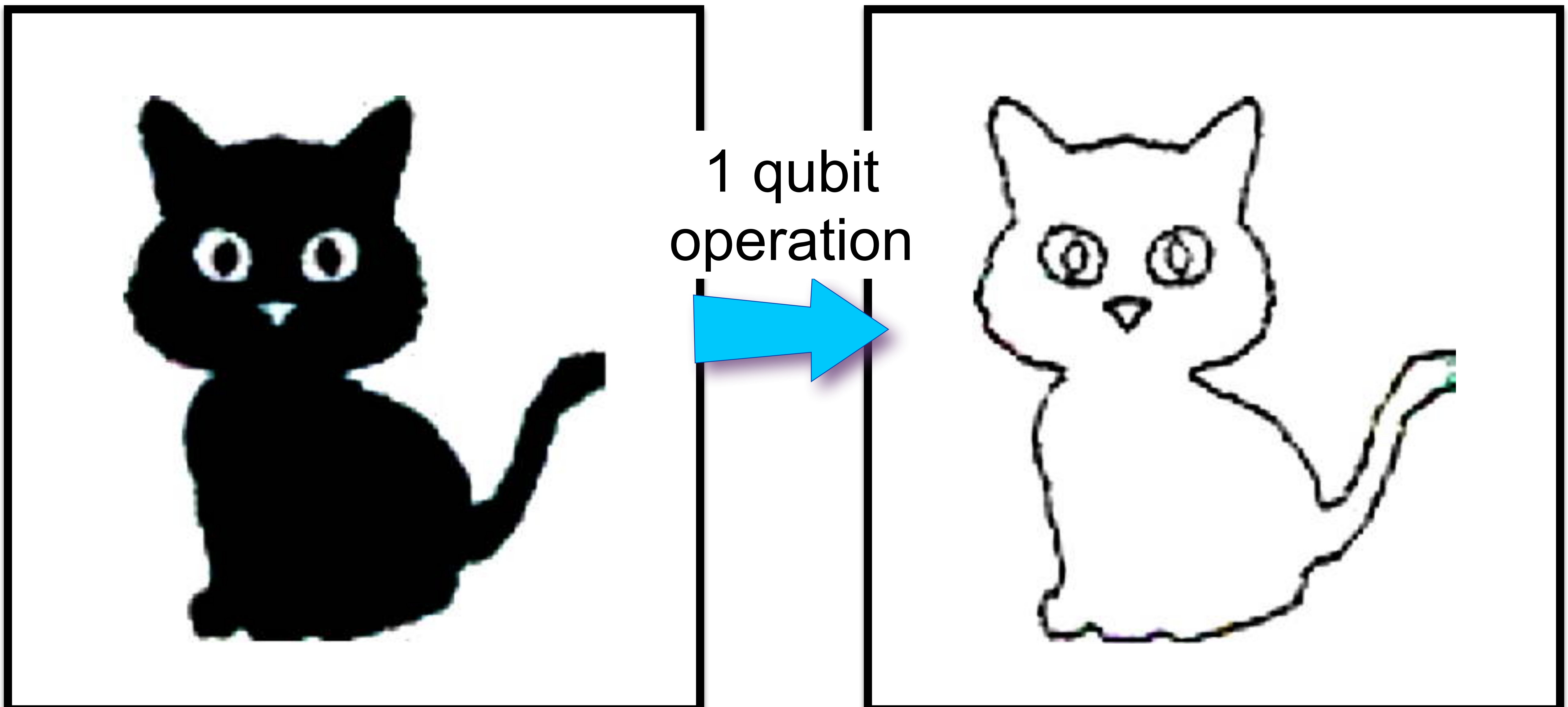
Potential Applications



Phys. Rev. X 7, 031041 (2017).

Quantum Image Processing

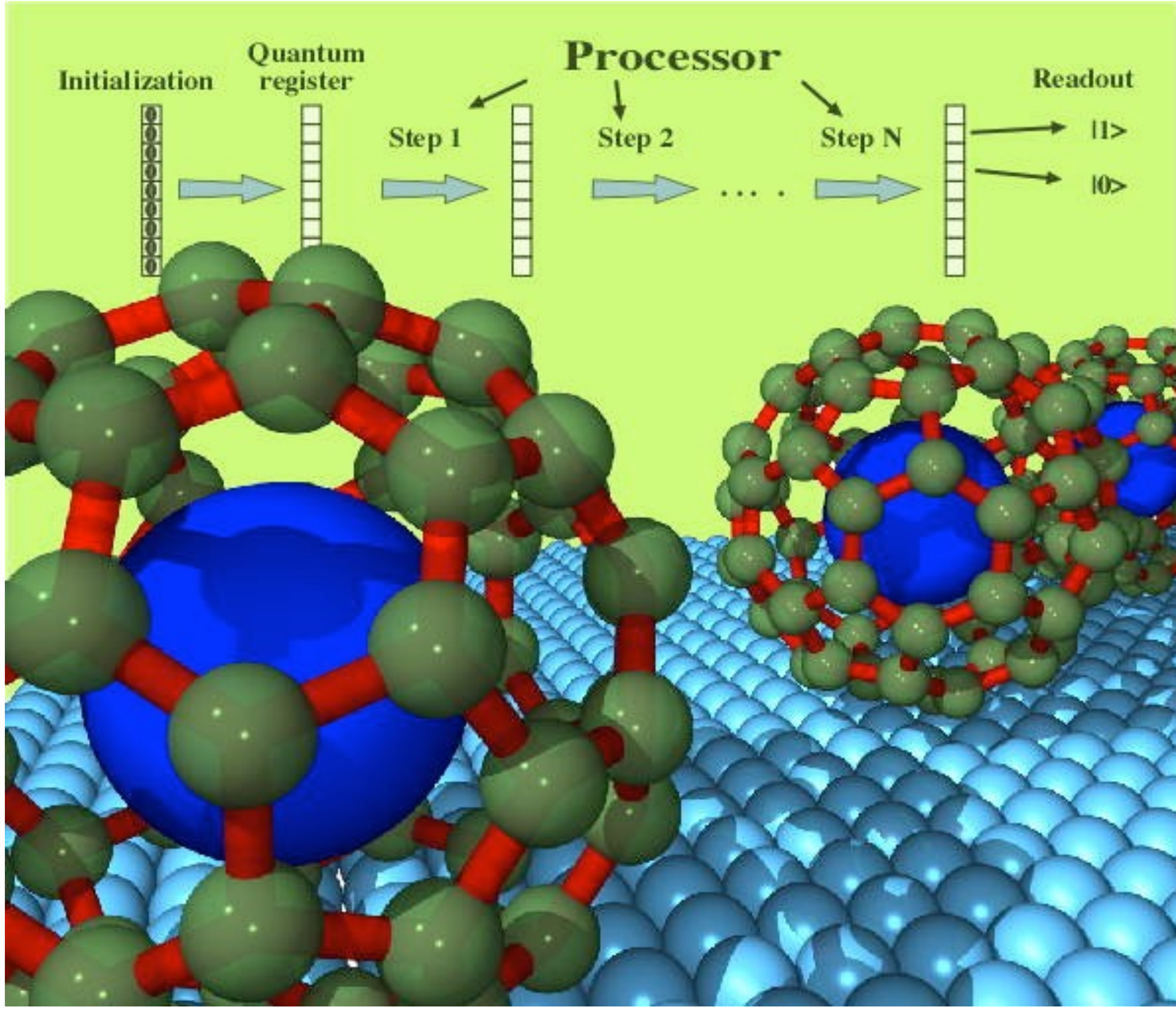
Task: detect border between 2 colours



Phys. Rev. X 7, 031041 (2017).

More Details ?

Joachim Stolze / Dieter Suter
Quantum Computing
A Short Course from Theory to Experiment



2. Edition - 2008
265 Pages, Softcover
ISBN 3-527-40787-1
Wiley-VCH, Berlin

Other textbooks:
http://e3.physik.uni-dortmund.de/~suter/Vorlesung/QIV_WS15/qcomplit.pdf

Conclusions

- Physics set limits on the performance of computers
- Limits differ for quantum / classical
- Quantum computers can outperform classical computers for some problems

Thank you for your attention !