The long road of Quantum Computing

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Tutorial

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Outline

Evolution of thoughts : from corpuscles to quantum world

Quantum Information and Quantum Computers

Various implementations : present status

Future challenges

Conclusions

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Evolution of thoughts : from corpuscles to quantum world

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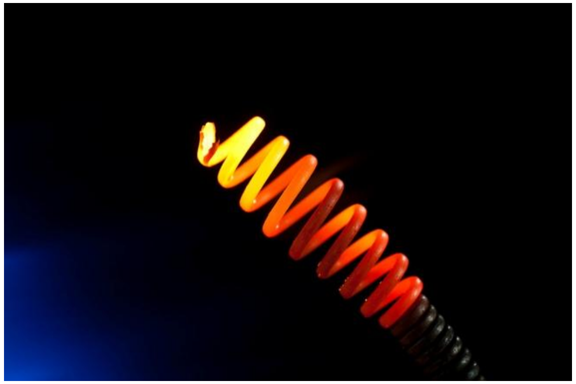
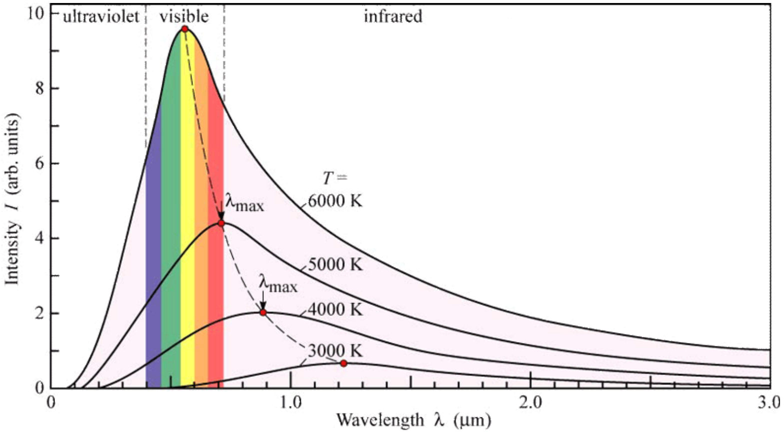
Max Planck and the black body radiation

- Colour changes with temperature
- Temperature T et frequency ν ?
- Thermal radiation and oscillators in equilibrium :

$$E = n\,\mathrm{h}\nu \;\propto 1/\lambda$$





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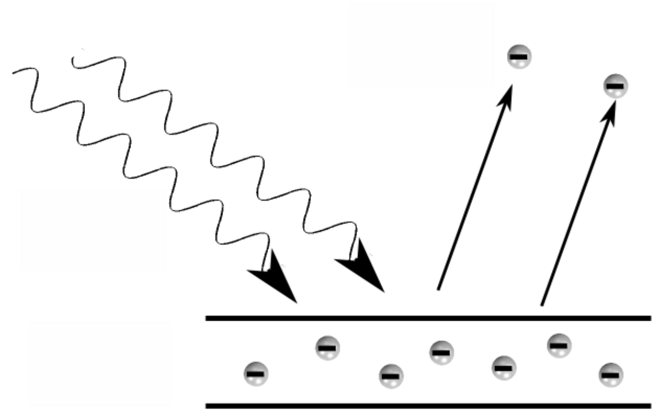
Evolution of thoughts : from corpuscles to quantum world

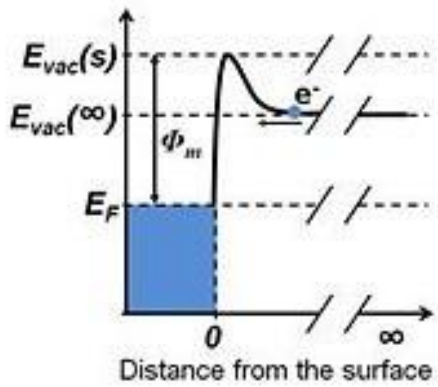
Albert Einstein : the photoelectric effect



- Generalisation to light
- Photovoltaic and photoelectric effects
- Contradicts the 2nd law of thermodynamics

  Entropy

ϕ = hν = work function



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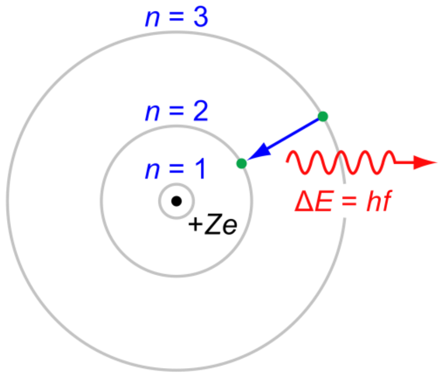
Evolution of thoughts : from corpuscles to quantum world

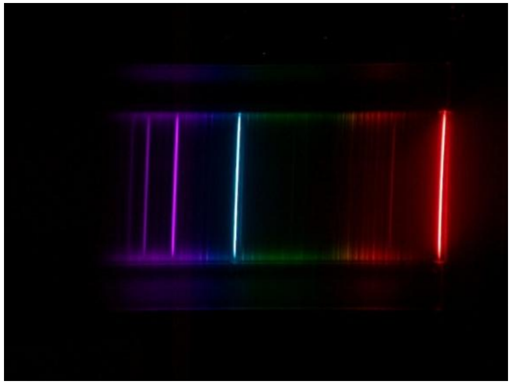
Bohr : atomic model

- Failure of Rutherford's model



- Atomic level quantisation

- Emission spectrum of hydrogen :



  - Discreet frequencies (series)
  - Hot gas emits photons (astrophysics)

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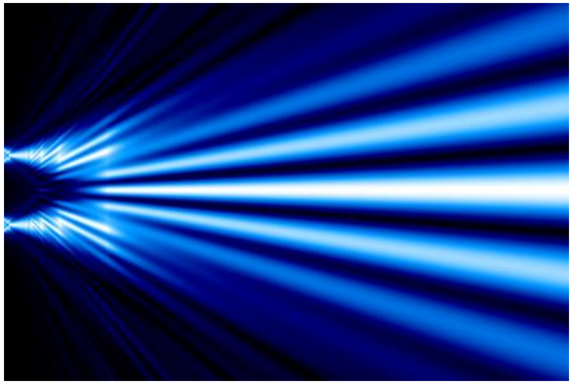
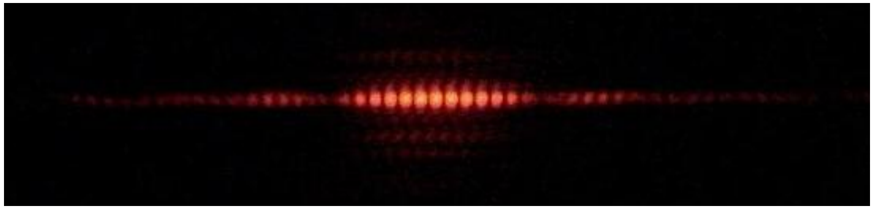
Evolution of thoughts : from corpuscles to quantum world

Young slits

- Generalisation to particles (γ, e-)



- Constructive and destructive interferences
- Wave-corpuscle duality



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Evolution of thoughts : from corpuscles to quantum world

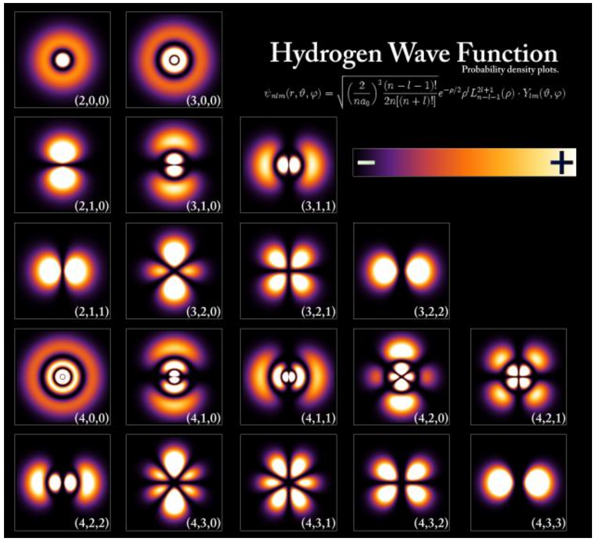
Erwin Schrödinger

- Atoms are waves, their states are wavefunctions

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\frac{-\hbar^2}{2\mu}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t)$$

- Probability (*t*, *r*)

$$|\Psi(x,t)|^2 = \rho(x,t)$$



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Copenhague interpretation

- A system is described by a wavefunction
- The wavefunction is described by the Schrödinger’s equation
- One can only measure a probability
- Uncertainty principle : $\Delta x \cdot \Delta p_x \geqslant \frac{\hbar}{2}$ $\Delta E \, \Delta t \geq \frac{\hbar}{2}$
- Matter is both corpuscles and waves (experiments)
- Quantum aspect disappears with size ???? (dipole interaction)

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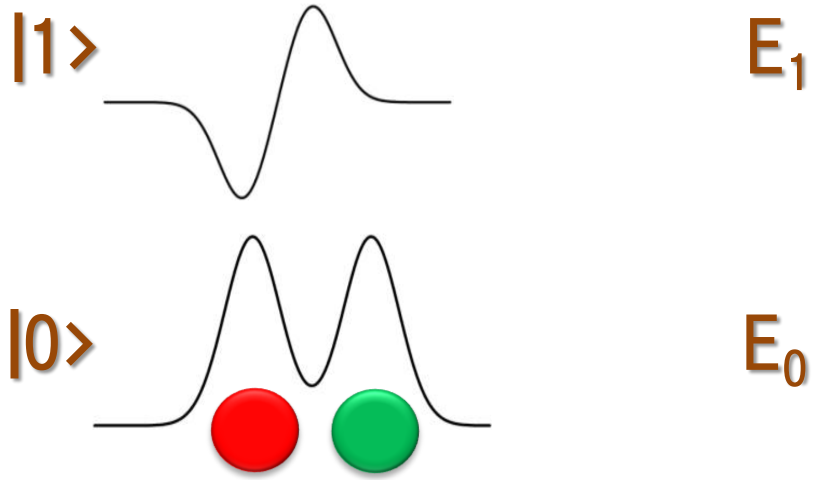
Quantum entanglement

- Pauli exclusion principle : not 2 e- in the same state
- Quantum superposition :
  - $\{ \Psi_1 , \Psi_2 \} \rightarrow | \Psi_{1+2} > = \alpha | \Psi_1 > + \beta | \Psi_2 >$
  - $\alpha^2 + \beta^2 = 1$
- H_2 molecule: bonding / antibonding



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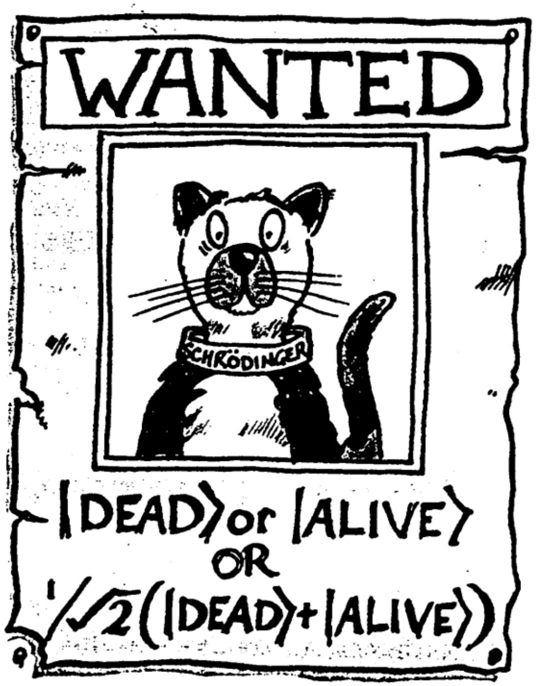
Schrödinger's cat, predictability

- Radioactive disintegration decides on the cat's fate
- Notion of observation :
  - **Interaction** with classical world
  - **Projective measurement** on eigenstate
  - **Collapse** of the wavefunction
- Realism, complexity of QM
- Coherence (T_2), many worlds



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Weak measurements (! Dispute !)

- How to measure without destroying ?
- Weak interaction between quantum system / detector
  Strong measurement on detector
- Final state is **NOT** an eigenstate
- Contradiction with QM ?

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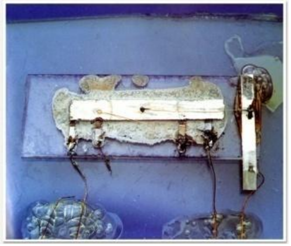
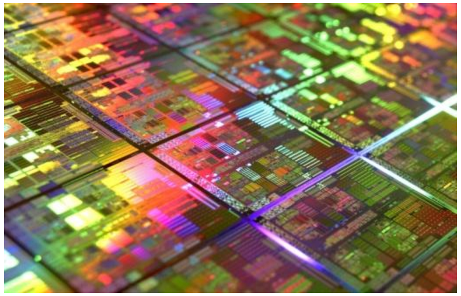
Feynman : towards practical use…

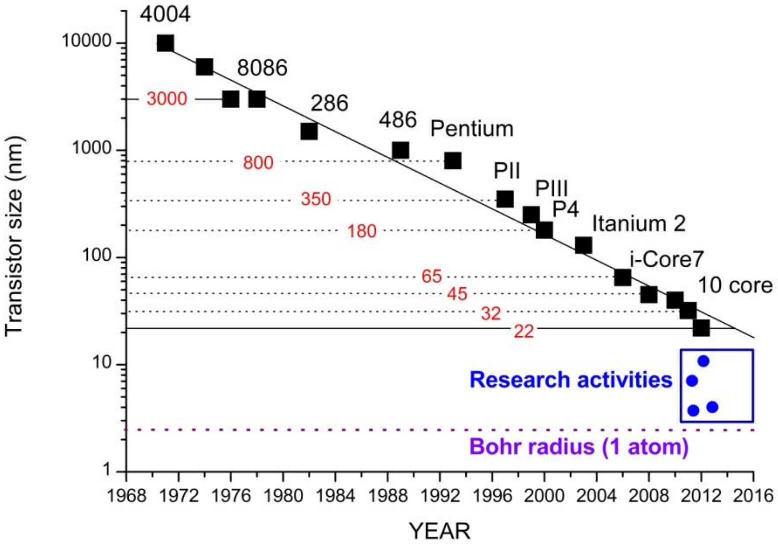
- 1958 : First integrated circuit





- 1959 : Possibility of manipulating and creating nanoscale objects

- 1965 : Moore's law
  Business argument



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Quantum Information And Quantum computers

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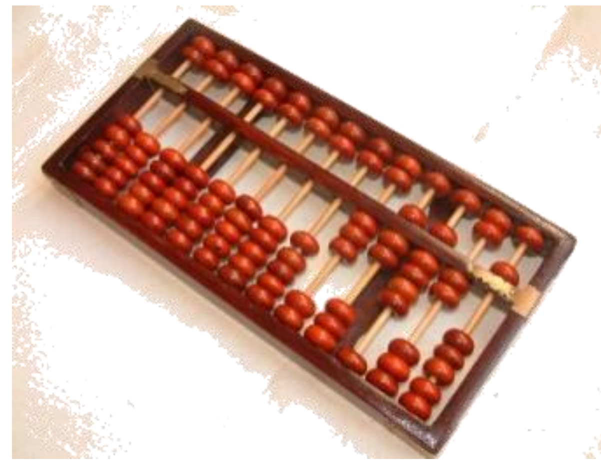
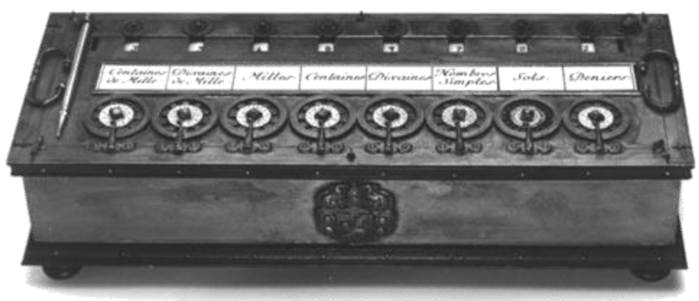
Quantum Information And Quantum computers

2400 BC – 1900 : mechanical power

- Abacus (+, -)



- Pascal (+, -)



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2400 BC – 1900 : mechanical power

- Loom machine : Card, storage

  First US census

- Babbage : Differential equations

  Analytical machine

- QWERTY (stuck rods)

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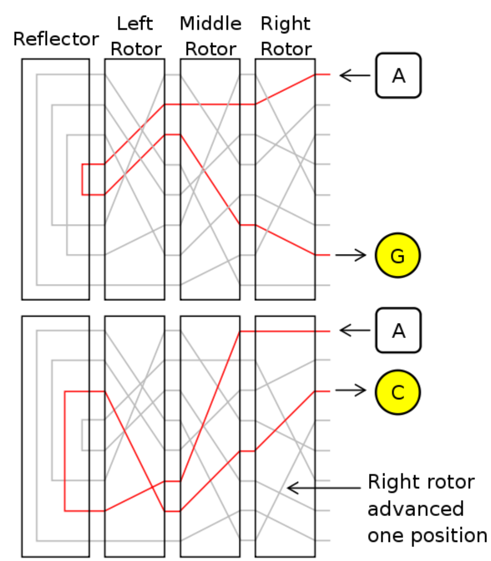
1900-1940 : electro-mechanical power

- Enigma : WWII, U-boats
  - 3 rotors on 26 positions
  - 1 reflector
  - Electrical circuits / Pressed key
  - Cryptography



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1910-1950 : Discharge tubes

- Replacement of metallic parts
- Parts : glass tube, vacuum, 3 electrodes

- Principle : Electron beam deflected by central electrode

  Modulation of current, conditions on-off or 0-1

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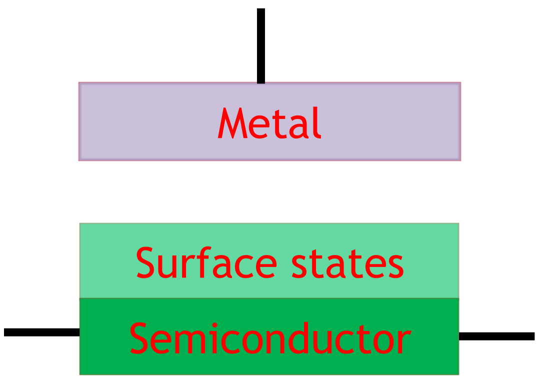
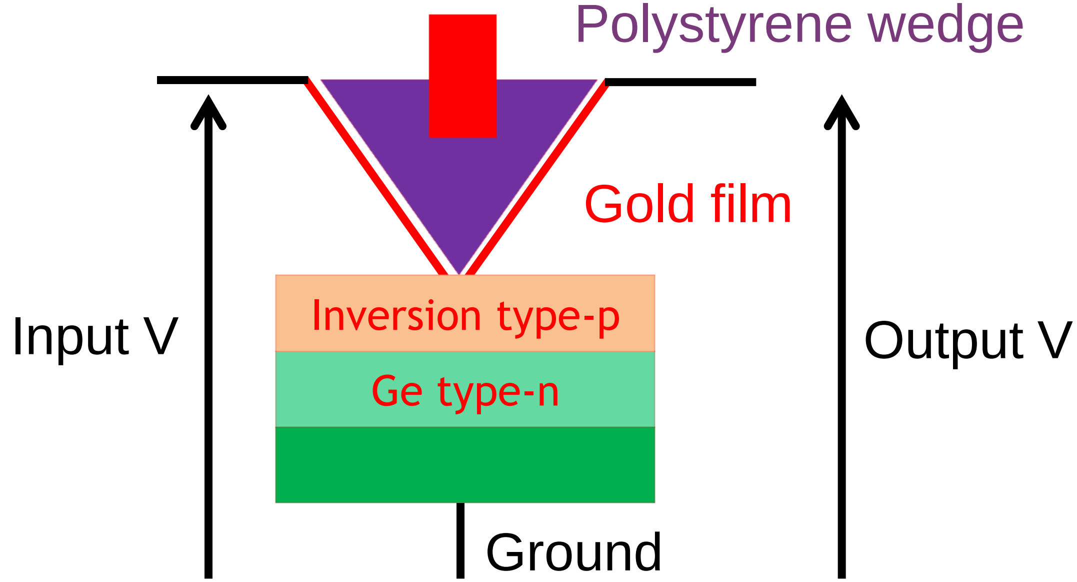
1910-1950 : Discharge tubes

- Glass bulbs : duration, quality, complexity, cost
- Bardeen (1947) and Shockley’s mistake





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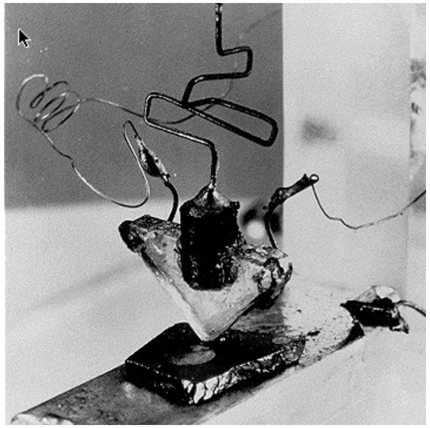
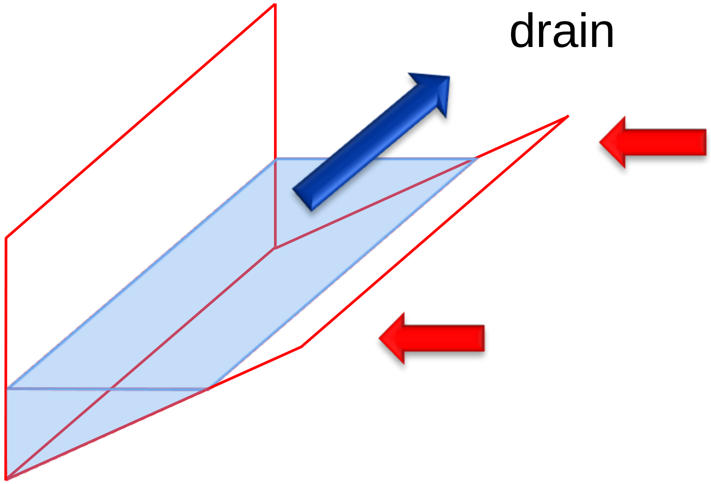
1947 : Invention of transistor

- Transistor : principles





Reduction in size and cost ➔ integrated circuits ➔ computers

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Quick history

Years	Architectures	Technologies	Applications
1935		SEM	BBC broadcast
1947	Ge Transistor		
1958	1st integrated circuit		
1960	1st MOSFET	MBE, e-beam	1st IBM computer
1962			1st laptop
1973	10 mm		CPU 16 bits
1980	MicroProc. GaAs	Laser photolithography	Family computer
1987	Organic FET		
1993	1st SET, 800 nm		
2004	Graphene		
2007		He Orion	
2009	45 nm		Smartphone
2014	22 nm		

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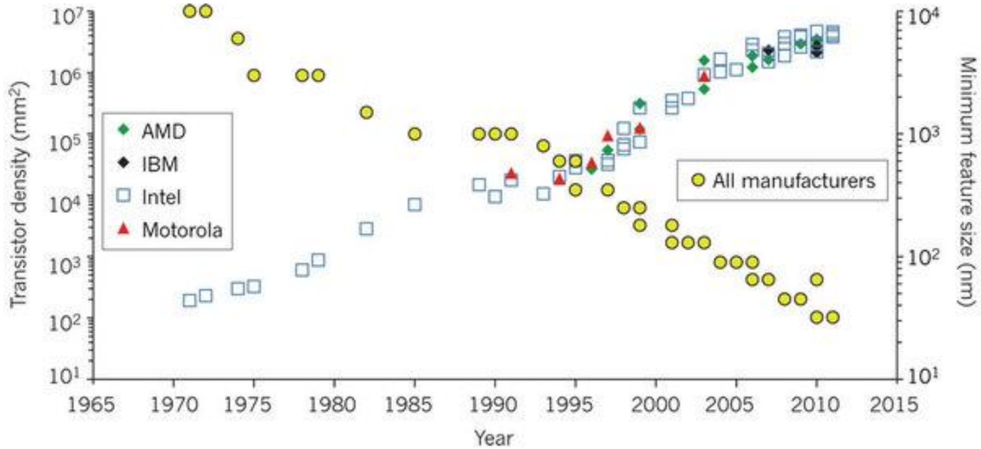
Size of transistors : Moore's law

- Continuous reduction in size : 1 cm ➔ 32 nm (22 nm in 2014)



Business model, not scientific

More and more calculus, more complex and longer

Increase in density : calculation power

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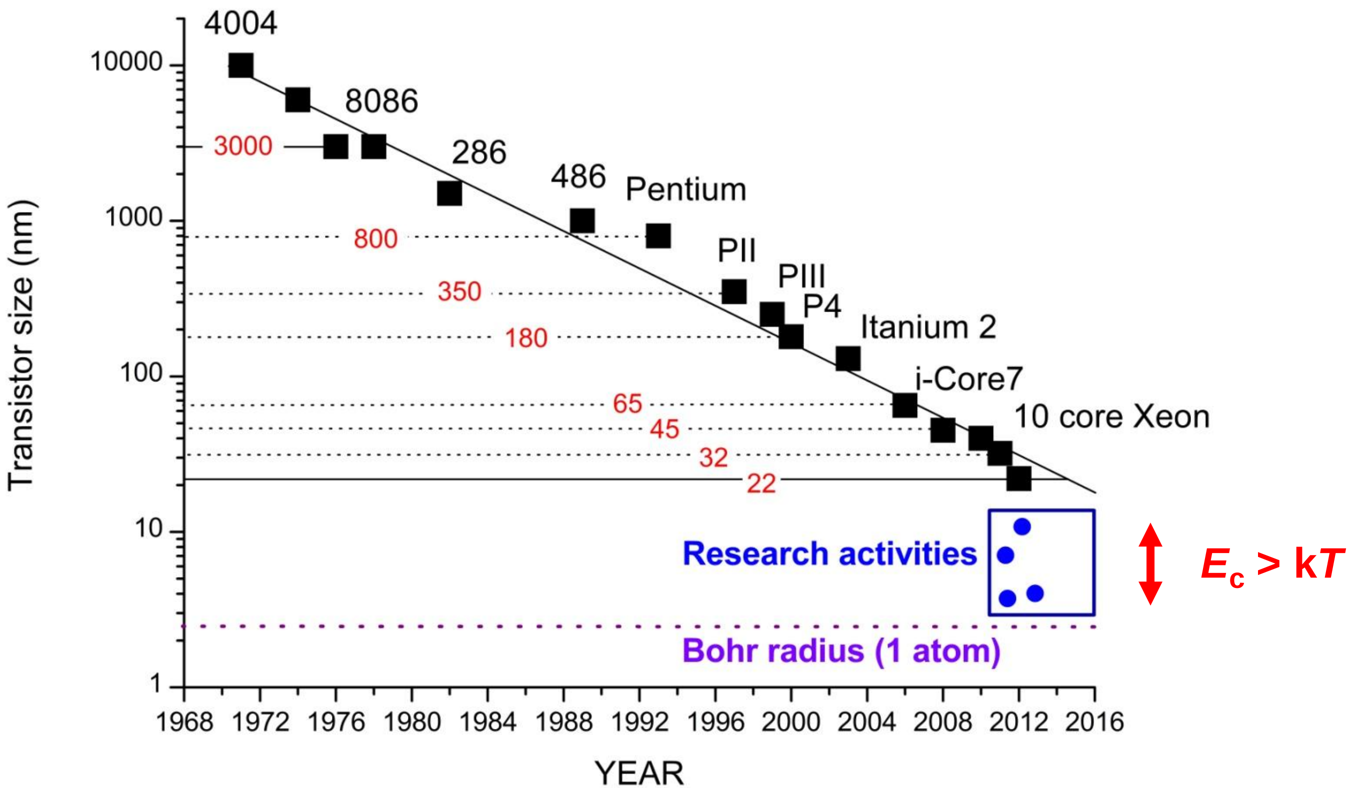
More than Moore

- From classical to quantum…



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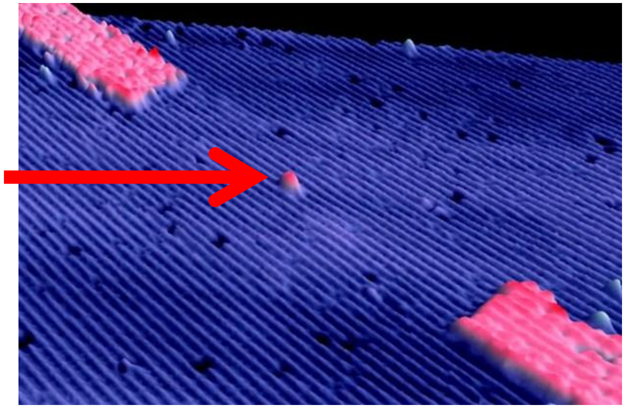
Problem of decrease in CMOS size

- Technology problem : atomic dimensions :



  - reproducibility (impurities and scalability)
  - industrial fabrication

Engineering problem : 3D integration :

  - connections
  - heating, efficiency

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Feynman and the quantum computer

- Theoretical problem, parasitic quantum and nanoscale properties

  L ➔ ξ μ ➔ τ n_{e-} ➔ N = 1, 2, …

- Quantum system :
  - Exponential size of Hilbert space
  - Classical computer cannot simulate it
  - Quantum computer uses QM properties

  N = 2 ➔ a and b : a, b, a+b, a-b 2^2 states, matrix 4 x 4

  N = 3 ➔ a, b and c 2^3 states, matrix 8 x 8

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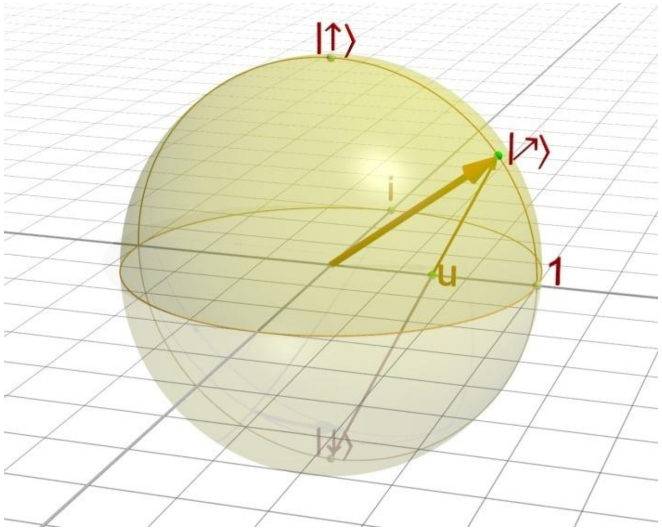
Notion of qubit

- **Qu**(antum) **bit** : 2 quantum states
- Quantum operation, unitary operator (Bloch sphere)

$$| \psi > = \alpha \; | x > + \beta \; | y > + \gamma \; | z > = U(\theta, \phi)$$

X Gate (1 qubit, π) : |0> ➔ |1>
|1> ➔ |0 >

CNOT (2 qubits) : | 00 > ➔ | 00 >
| 01 > ➔ | 01 >
| 10 > ➔ | 11 >
| 11 > ➔ | 10 >



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Concept of entanglement

- Example : 2 spins

  $|\uparrow\rangle, |\downarrow\rangle \rightarrow |\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle, |\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle$

  projective measurements (spin reversal, photon polarisation)

- No communication via a share in entangled states

  No faster-than-light transmission

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Concept of cloning and teleportation

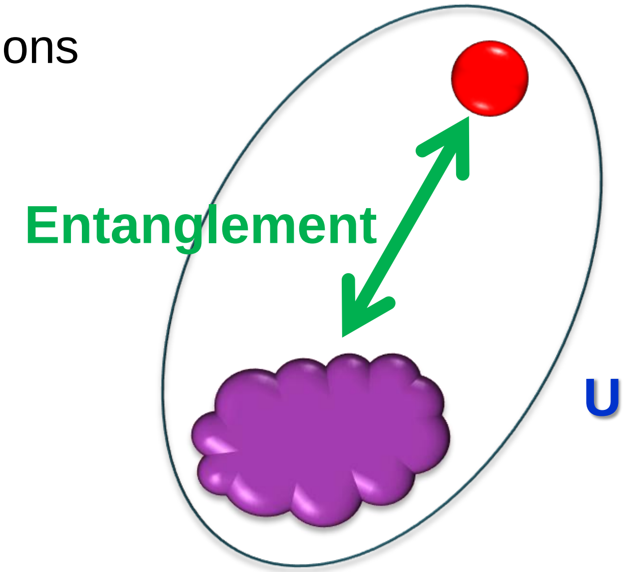
- No-cloning :
  - No identical copies of unknown quantum state
  - Only orthogonal states are possible
  - No classical techniques of error corrections

  - Imperfect copies possible

    Unitary operation of the system

    Some cloned properties

    Quantum protocol attack



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Concept of cloning and teleportation

- No teleportation :
  - Information **already shared** : entanglement creates states
  - No precise measurements (some part of uncertainty, Heisenberg)
  - No reconstruction of quantum states via classical states

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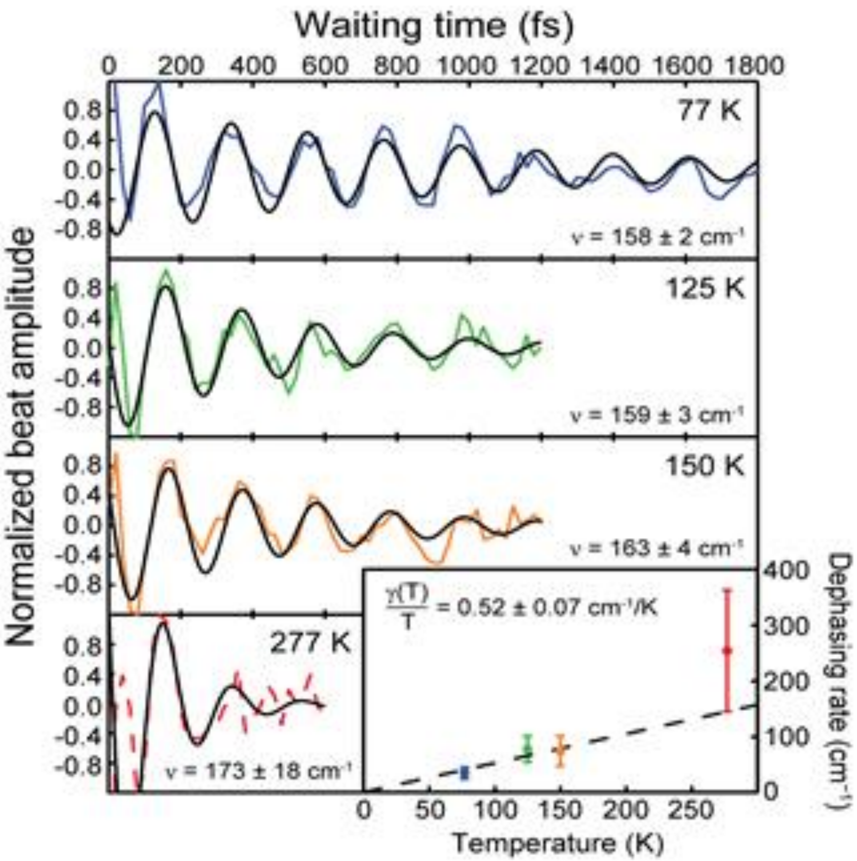
Decoherence and coherence

- Natural loss of entanglement
- Coupling with classical environment
- Depends on system, measurement type
- Maximum time for operations (T_2)



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Quantum cryptography

- Breaking 1024 bits RSA : time
- Quantum algorithm faster (TRULY parallel)
- No possibility to obtain information by third party
- Crypting : secure transmission ???
  weak measurement, noise…

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Applications

- Factoring large numbers (Shor algorithm)

  Classical (reduction) and quantum (acceleration)

  $(\text{Log } N)^3$ instead of $\exp(\log(N)^{1/3})$

- Banking and financial transactions

  Scientific calculations (Astronomy, genome)

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Various implementations : present status

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Various implementations : present status

Industries vs Universities

- Industrial approaches : silicon, integration, cost, scaling
- Scientific approaches : GaAs (optics, e-),
  superconductors (Josephson junctions)
- Mixed approaches : DNA, molecules, biophysics
- Financial approaches : nano-objets but classical operation
  D-wave (quantum annealing, adiabatic)

A nano-object is not necessarily quantum !!!

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Various implementations : present status

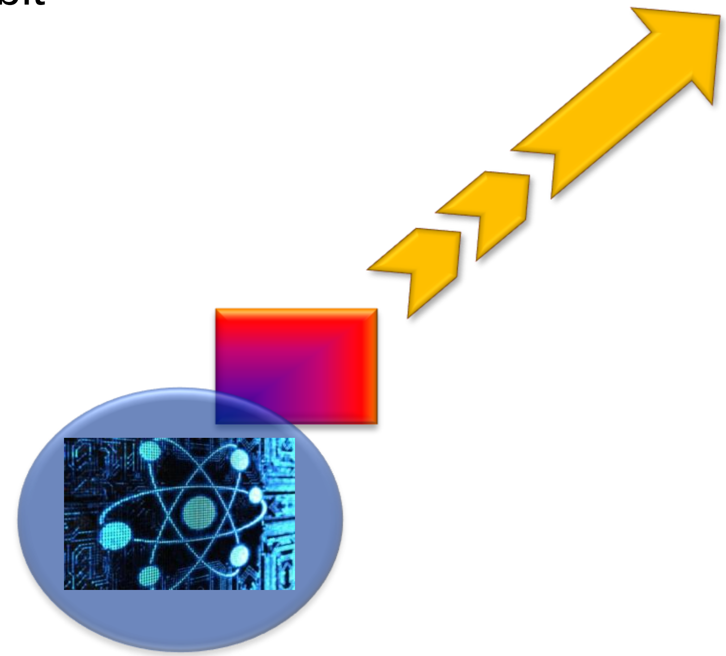
Qubits types and long-range communication

- Purely solid : electron-electron or local qubit

  Purely optical : photon-photon or flying qubit

  Mixed : electron-photon

- Long distance communication :
  - Local entanglement
  - Information conversion
  - Coherent transmission



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Various implementations : present status

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Local qubits : Kane model

- Local conditions :

Define…	the qubit states
Initialise…	the computer in a defined state (***B***, ***E***…)
Determine…	a set of universal operations
Have…	a long coherence time
Read…	the result with high probability
Realise…	a large number of qubits

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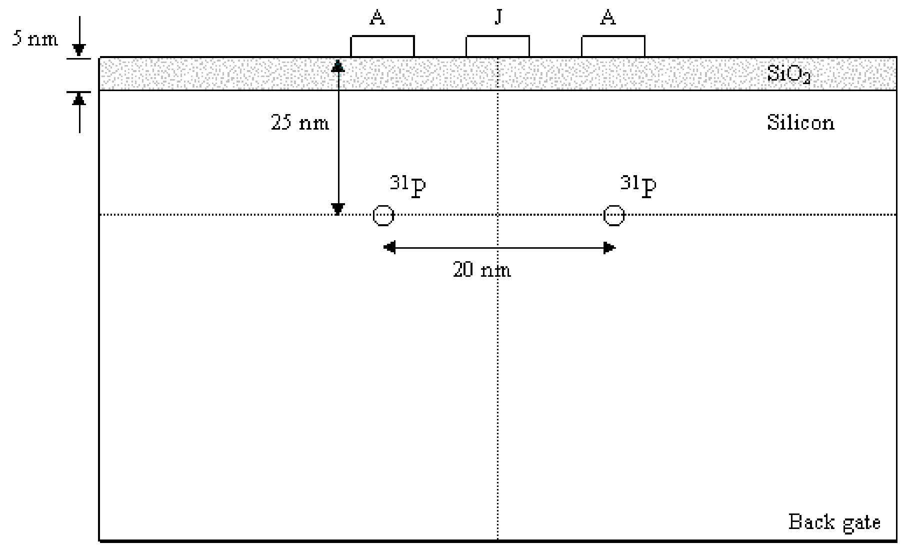
Various implementations : present status

Local qubits : Kane model

- 2 coupled P donors (hyperfine interaction)

  2 types of gates A, J



- MOS structure

  Exchange interaction

  Modulation of interactions

  Distance to be adjusted

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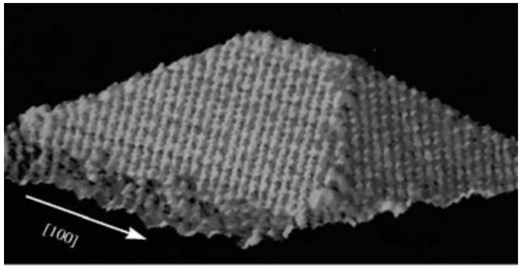
Various implementations : present status

Semiconductor qubit

- Quantum dots (number of e- or energy levels)

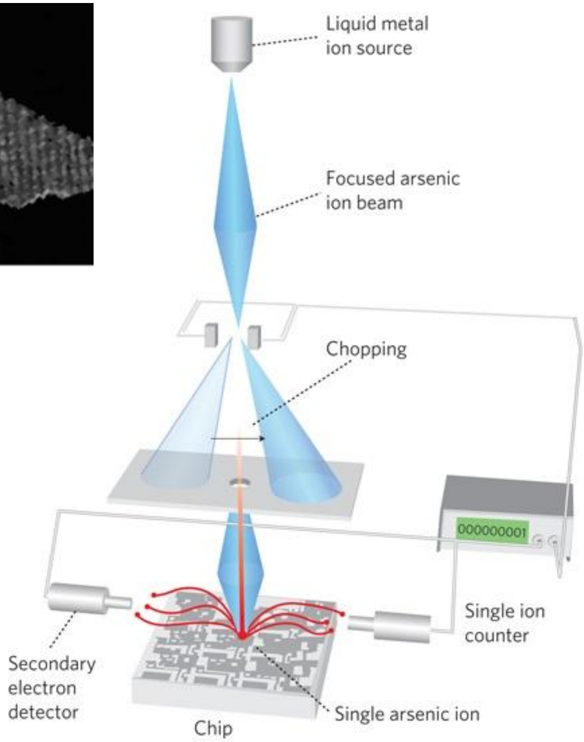


N = 1-2

T_2 = 1-5 ms (III-V)

T_2 = 100 ms in silicon

- Mono- or bi-atomic implantation



N = 1

T_2 = 45 s (nuclear or electron state)

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Various implementations : present status

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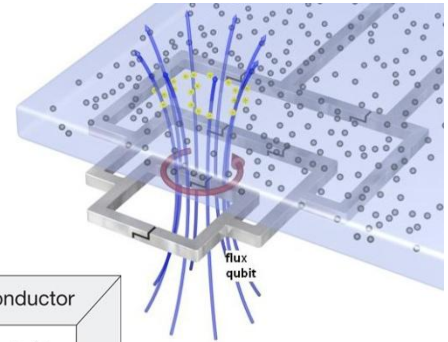
Superconducting qubits and others

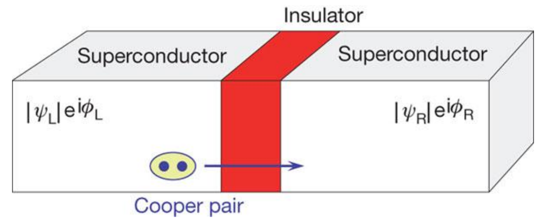


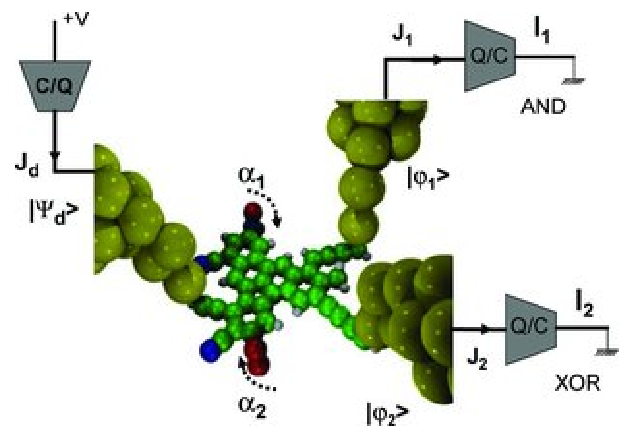
- Josephson junctions (charge, flux, phase)

  Orientation of current

  N = 5, T_2 = 20 μs

  Factorisation of 15





- Molecule (charge, spin)

  Orientation of molecule by E

  N = 3, T_2 = 3 ms

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Various implementations : present status

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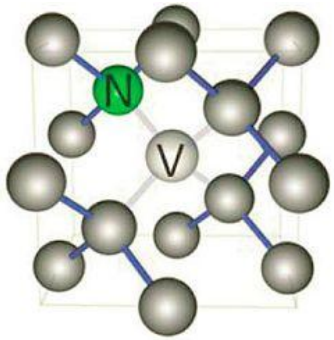
Superconducting qubits and others

- NV centre (NV^0, NV^-)



Defect due to N in diamond

N = 2, T_2 = 100 ms (2012), 1 s (2013)

- Ion traps

Atoms are spatially confined, Coulomb interaction

CNOT in 1995

N = 14, T_2 = 10 s

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Flying Qubits

- Kane's extra conditions :

  Coupling… a local qubit to photons (GaAs, Si ?)

  Propagating… photons in a coherent way (fibres…)

- Principle :

  Polarisation of photons (H, V or circular)

  Photon pairs, bi-refringent lenses

  $N = 14$, $T_2 = 4$ ms

  Some optical quantum networks and successful transmissions

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Various implementations : present status

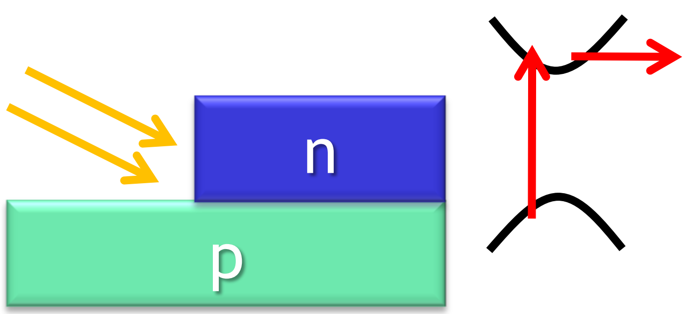
Interaction localised - delocalised

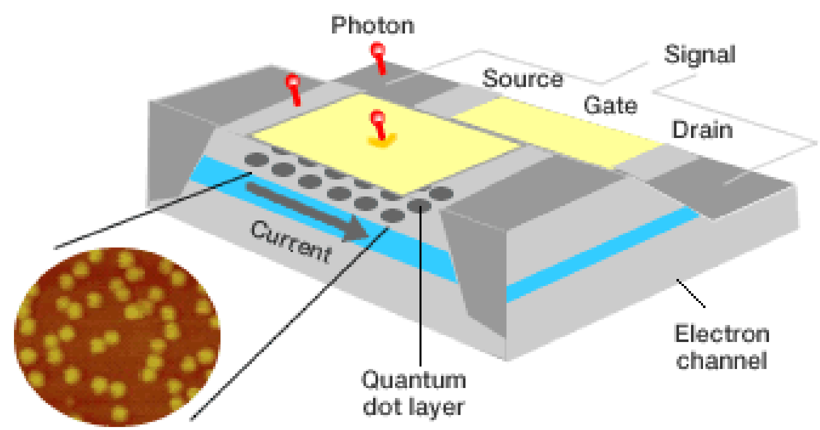
- <u>Single photon emitters and detectors</u> :

  GaAs : direct band-gap, well controlled growth

  Realised in 2005, impurities

- Transistor detects photon absorption by quantum dots





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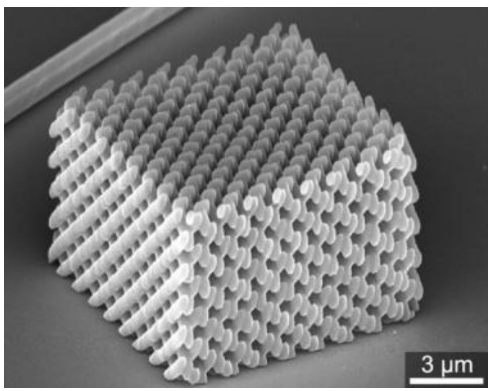
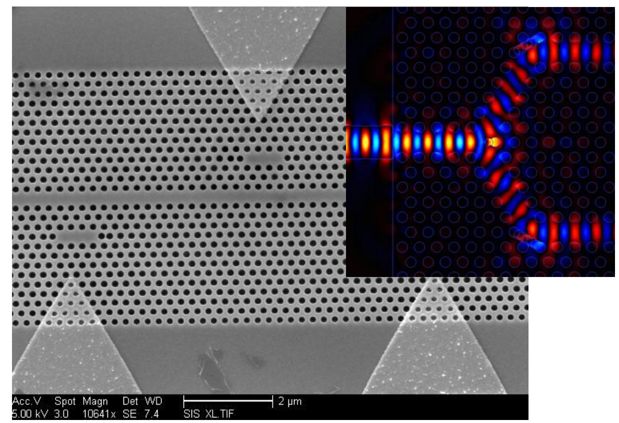
Various implementations : present status

Other trends and technologies

- Photonic crystals : quantum dot in a cavity, optical circuits





- Quantum bus : displacing qubits over mm (not much, SAW)
- Future : mix of technologies (Si, GaAs, bio…)
- Classical calculations on nanoscale objets : QCA (cellular automata)

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Future Challenges

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Future challenges

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Solutions and problems

- Coherence ➔ **No more a problem, T_2 very large !!!**
- Large scale production ➔ **Depends on approaches**
  ➔ **Necessary selection**
- Displacing information ➔ **Optical fiber (quality)**
  ➔ **Repeaters (cloning)**
  ➔ **Qubit buses (μm)**
- Unbreakability ➔ **Quantum noise study (weak measurements)**

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Conclusions

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Conclusions

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Quantum computing

- A clear technological revolution that needed :

Quantum mechanics AND **Advanced computers**

- Quantum information, Quantum cryptography

- Significant progress recently : scientific, technology & techniques
    - Single ion implantation, STM stability
    - Electron and nuclear spin control
    - Coherence time, dispersive readout (**PANEL on Tuesday**)

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Conclusions

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Advantages and inconvenients

- Advantages :
  - Secure communications ? (weak measurement, noise)
  - True parallel processing
- Inconvenients :
  - Decoherence (limited calculation/operation time)
  - Classical influence on quantum
  - Need for insulation (T_2~ 1 s but 10^9 operations)
  - No possibility for storage (no cloning)
- Not enough developed : Integration / interface solid-optical

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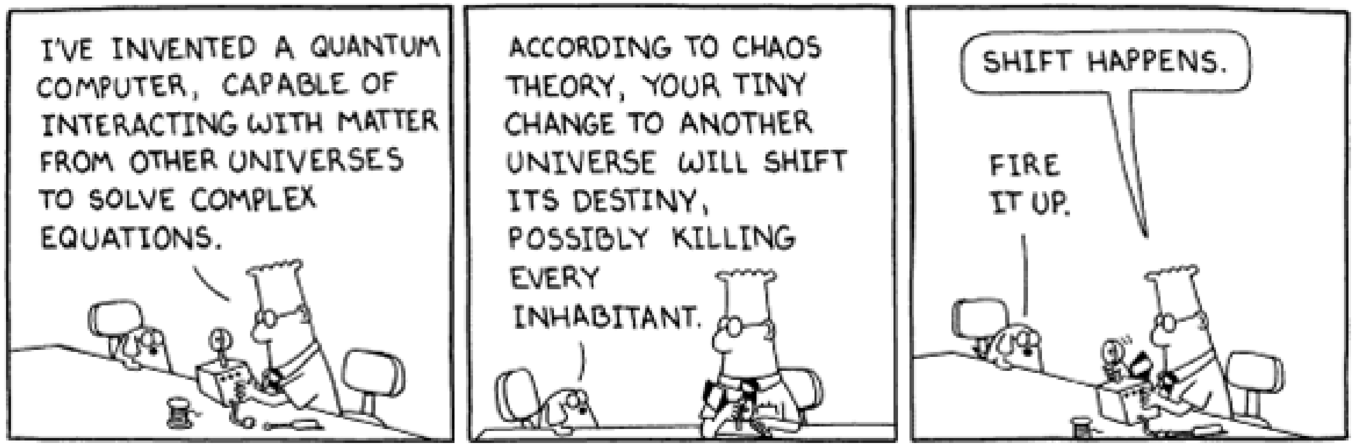
Conclusions

Final bits

- **Round table on Thursday :**
  - Measurement and entanglement
  - Long distance entanglement (quantum on μm scale) ?
- Could we really build fully a quantum computer ? Dream or reality ?



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