Physics of Condensed Matter I

inżynieria nanostruktur

1100-4INZ`PC

Faculty of Physics UW

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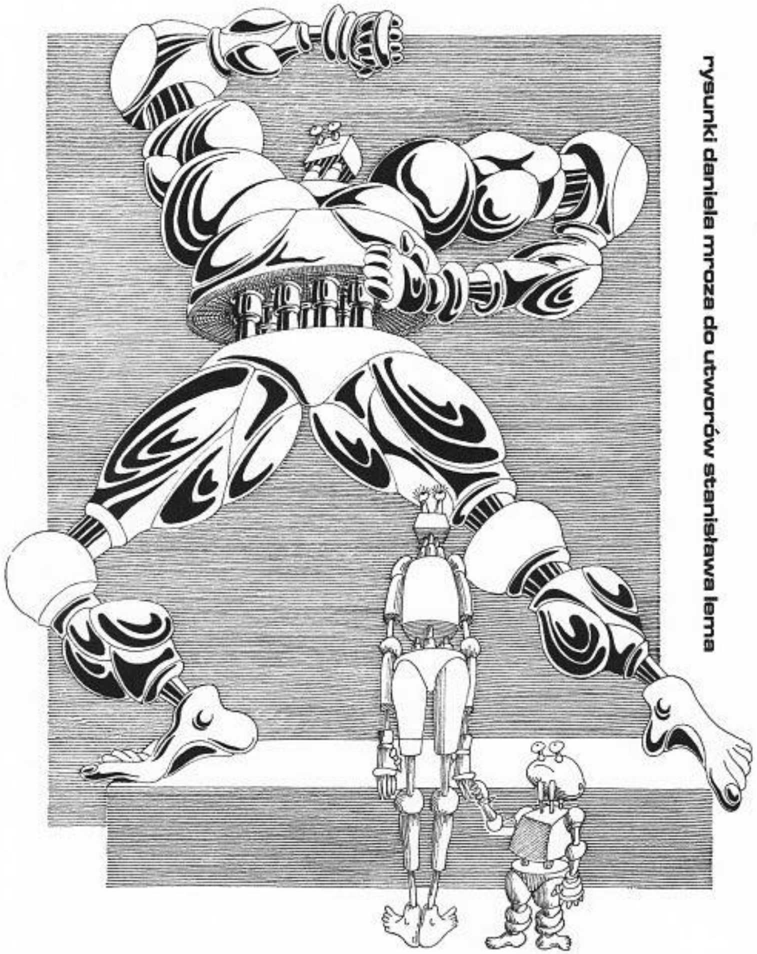
Summary of the lecture

1. Quantum mechanics
2. Optical transitions
3. Lasers
4. Optics
5. Molecules
6. Properties of molecules
7. Crystals
8. Crystalography
9. Solid state
10. Electronic band structure
11. Effective mass approximation
12. Electrons and holes
13. Carriers
14. Transport
15. Optical properties of solids



Summary of the lecture

1. Quantum mechanics
Revision of quantum mechanics: quantum states, quantum numbers, quantum well. Perturbation theory in quantum mechanics. Electric and magnetic field.

2. Optical transitions
Spin. Spin-orbit interaction. Magnetic ordering. Time-dependent perturbation theory. Electric dipole transition, selection rules.

3. Lasers
Einstein coefficients. Photo absorption, spontaneous emission and induced emission. Population inversion for laser action.

4. Optics
Revision of optics. Maxwell equations. Polarizability. Refractive index. Lorentz model od refractive index. Optical properties of metals, plasma frequency.

5. Molecules
Chemical bonds (sigma, pi). H2+ molecule. Born-Oppenheimer approximation. Hartree-Fock method. Linear combination of atomic orbitals. Diatomic molecules.

Summary of the lecture

6. Properties of molecules
Molecular spectra. Electronic, vibrational and rotational transitions for diatomic molecule.

7. Crystals
Chemical bonds, hybridization (s,p,d). Symmetry of bonds. Condensation. Crystal structure. Primitive translation vectors. Bravais lattice.

8. Crystalography
Basic elements of crystallography. Miller indices. Scattering of X-rays. Atomic form factor. Reciprocal lattice.

9. Solid state
Drude model of metals, mobility, conductivity. One-electron model. Hartree-Fock approximation. Periodic potentials and Bloch's theorem. Empty lattice approximation. Brillouin zones.

10. Electronic band structure
Tight-binding approximation, Linear Combination of Atomic Orbitals (LCAO). Electronic band structure.

Summary of the lecture

11. Effective mass approximation
kp perturbation theory. Effective mass. Electrons and holes.

12. Electrons and holes
Quantum statistics. Fermi-Dirac distribution. Bose-Einstein distribution. Fermi energy in solid state. Density of states in 3D, 2D and 1D.

13. Carriers
Carriers concentration: intrinsic. Doping. Acceptors and donors. Hydrogen-like atom model. p-n junction.

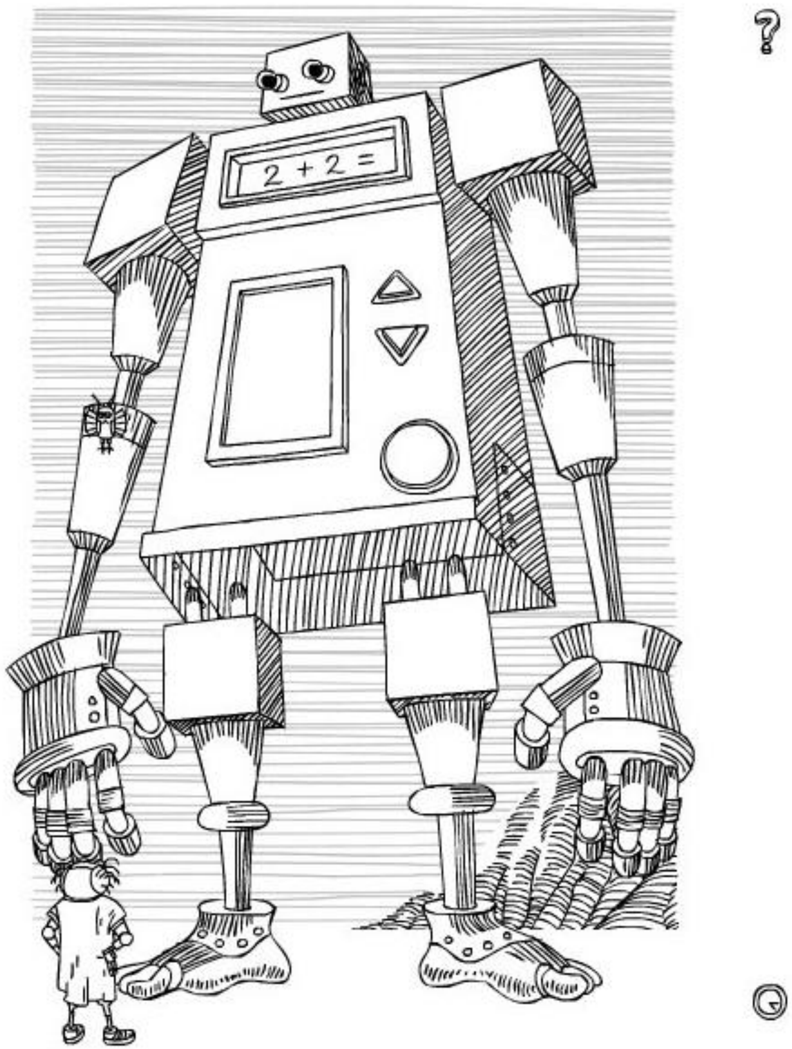
14. Transport
Carriers in external electric field. Carriers in external electric and magnetic field. Conductivity and resistivity tensors. Hall effect.

15. Optical properties of solids
Absorption edge. Join density of states. Excitons, trions in quantum wells. Quantum dots.

Assessment criteria:

Quiz (kartkówka) 20p.
2 tests (3 exercises) 2x30p = 60p
Activity in exercises (dr Aneta Drabińska) 20p
passing grades: minimum 50p/100p

Exam: final test (40p) and oral exam
oral exam – minimum 70p/140p



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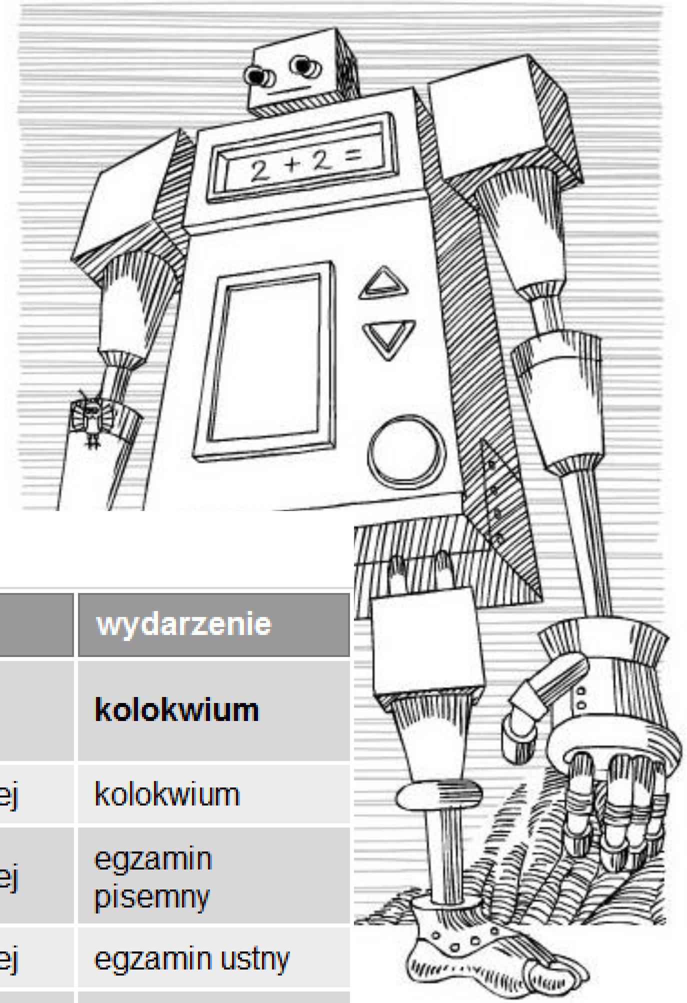
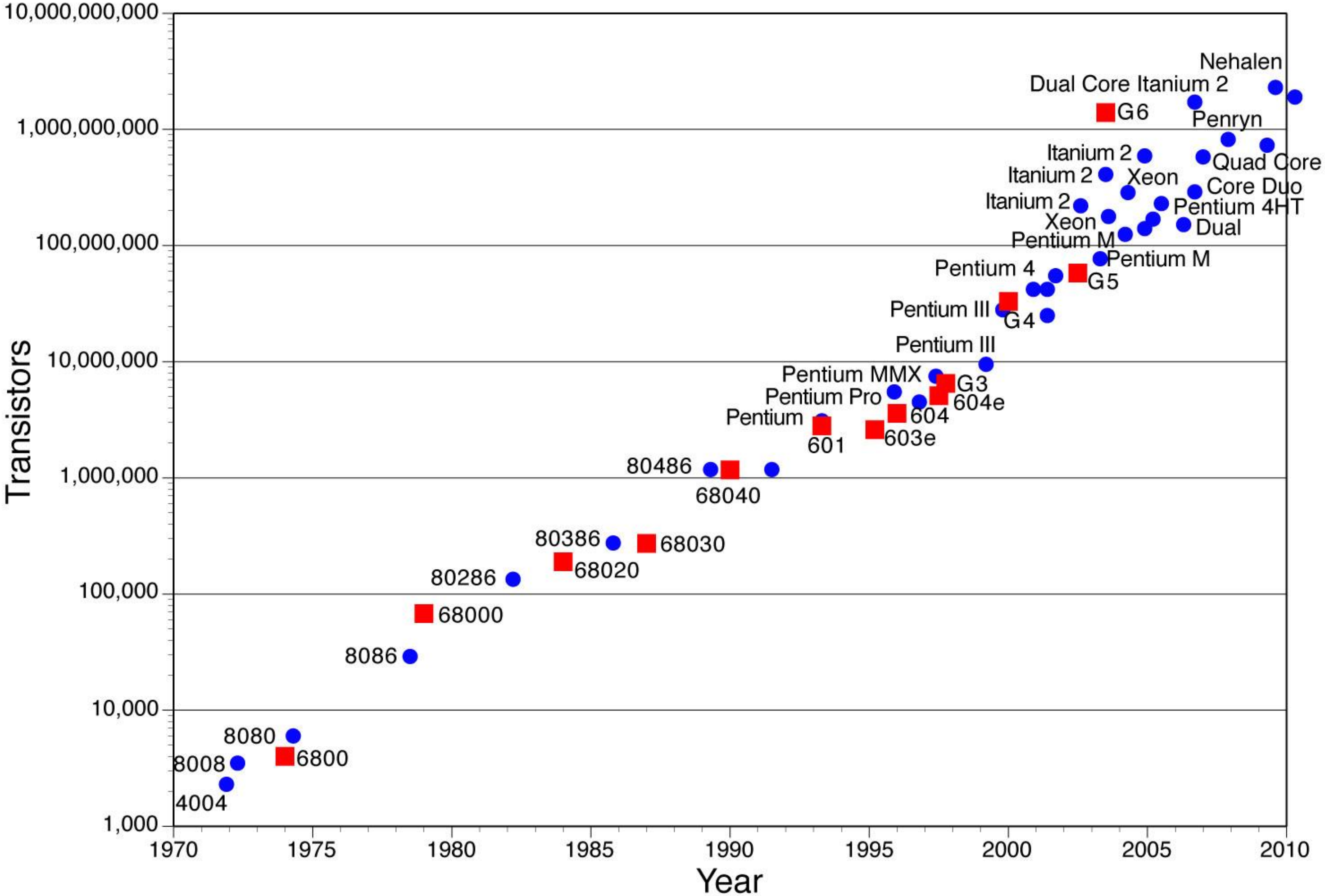


III rok inż. nanostr.

data	godziny	sala	przedmiot	wydarzenie
2015.11.16	**09:00 – 13:00**	**1.40**	**Fizyka materii skondensowanej**	**kolokwium**
2016.01.11	09:00 – 13:00	1.40	Fizyka materii skondensowanej	kolokwium
2016.01.29	14:00 – 17:00	Cyklotron A	Fizyka materii skondensowanej	egzamin pisemny
2016.02.01	09:00 – 13:00	1.37	Fizyka materii skondensowanej	egzamin ustny
2016.02.02	09:00 – 13:00	1.37	Fizyka materii skondensowanej	egzamin ustny

NANO era


Transistors
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Year
1970
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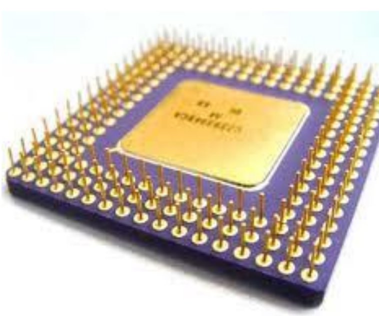
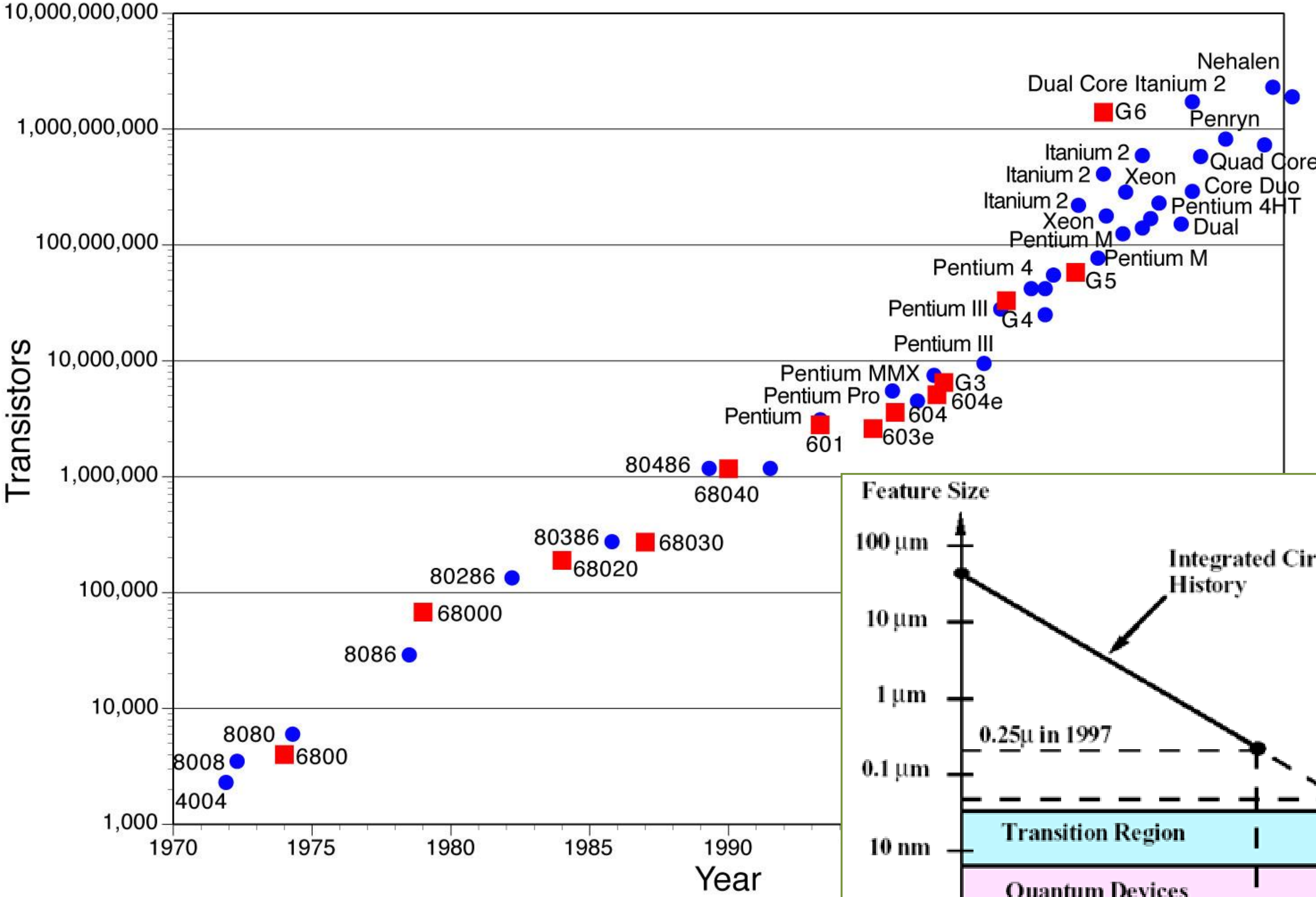
1985
1990
1995
2000
2005
2010
4004
8008
8080
6800
8086
68000
80286
68020
80386
68030
80486
68040
Pentium
601
Pentium Pro
603e
604
Pentium MMX
604e
G3
Pentium III
Pentium III
G4
Pentium 4
G5
Pentium M
Pentium M
Xeon
Itanium 2
Itanium 2
Itanium 2
Xeon
Dual
Pentium 4HT
Core Duo
Quad Core
Penryn
G6
Dual Core Itanium 2
Nehalen



NANO era


Transistors
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1970
1975
1980
1985
1990
Year
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8008
8080
6800
8086
68000
80286
80386
68020
68030
80486
68040
Pentium
601
Pentium Pro
Pentium MMX
604
603e
G3
604e
Pentium III
Pentium III
G4
Pentium 4
G5
Pentium M
Pentium M
Xeon
Itanium 2
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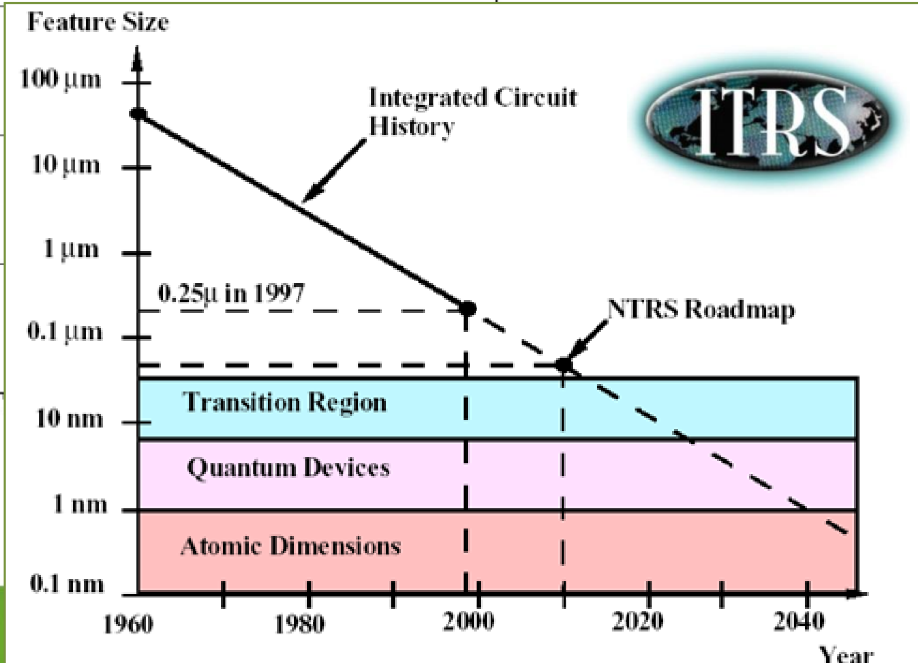
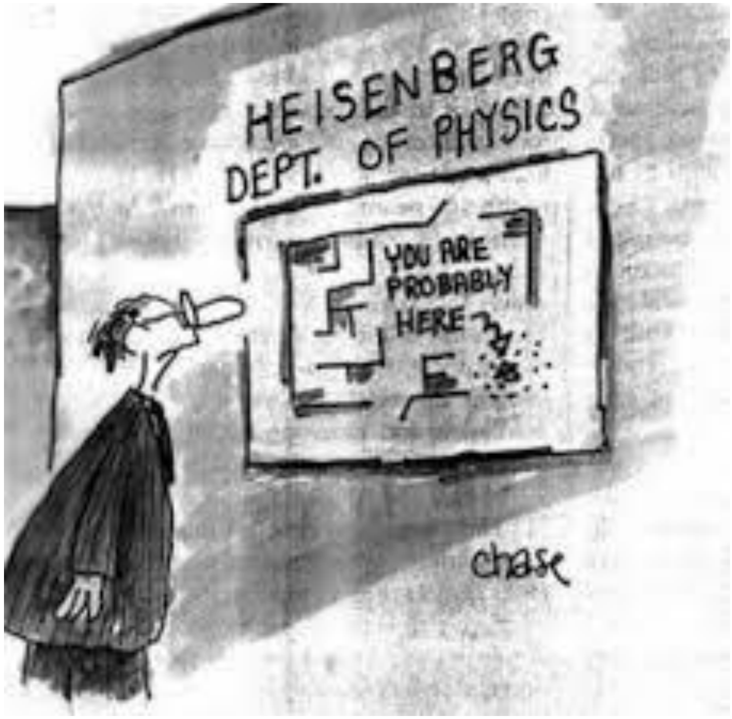
Pentium 4HT
Dual
Core Duo
Quad Core
Penryn
G6
Dual Core Itanium 2
Nehalen


Feature Size
100 µm
10 µm
1 µm
0.1 µm
10 nm
1 nm
0.1 nm
Integrated Circuit History
0.25µ in 1997
NTRS Roadmap
ITRS
Transition Region
Quantum Devices
Atomic Dimensions
1960
1980
2000
2020
2040
Year

Quantum mechanics

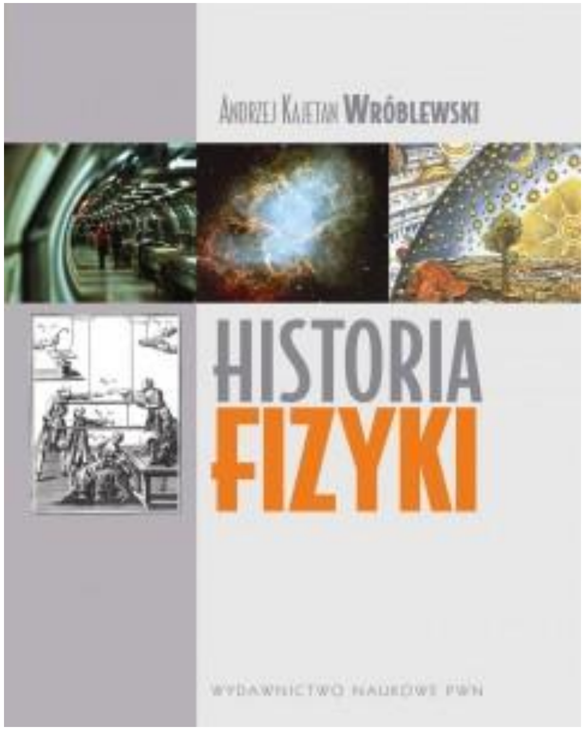


The history

History of physical sciences

1100-HPS-OG, 1101-3N`HPS

Prof. dr hab Andrzej Kajetan Wróblewski



Historia fizyki. Od czasów najdawniejszych do współczesności

Wydawnictwo Naukowe PWN

The Math and the Nature?

Scientific method:

The conversation with the Nature must be hold in the language of mathematics, otherwise nature does not answer our questions.

prof. **Michał Heller**

Dialog z przyrodą musi być prowadzony w języku matematyki, w przeciwnym razie przyroda nie odpowiada na nasze pytania.

prof. **Michał Heller**

The Math and the Nature?

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The history

Sir Isaac Newton (4 January 1643 – 31 March 1727)

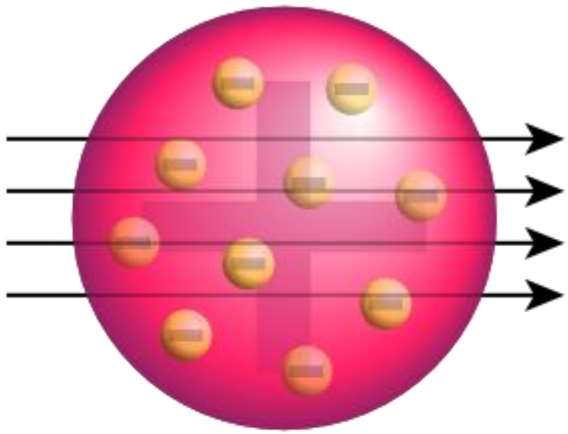
Michael Faraday, FRS (September 22, 1791 – August 25, 1867)

James Clerk Maxwell (13 June 1831 – 5 November 1879)

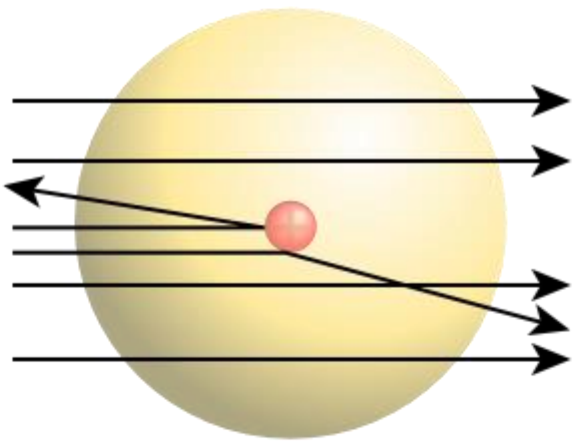
http://www-personal.umich.edu/~jbourj/money1.htm

The history

- In the XIX century: the matter is granular, the energy (mostly e-m) is a wave



The plum pudding model (J.J. Thomson 1904)



1909 gold foil experiment of Hans Geiger and Ernest Marsden.
Interpreted by Ernest Rutherford in 1911

http://rutherford.pl/informacje/doswiadczenie-rutherforda/

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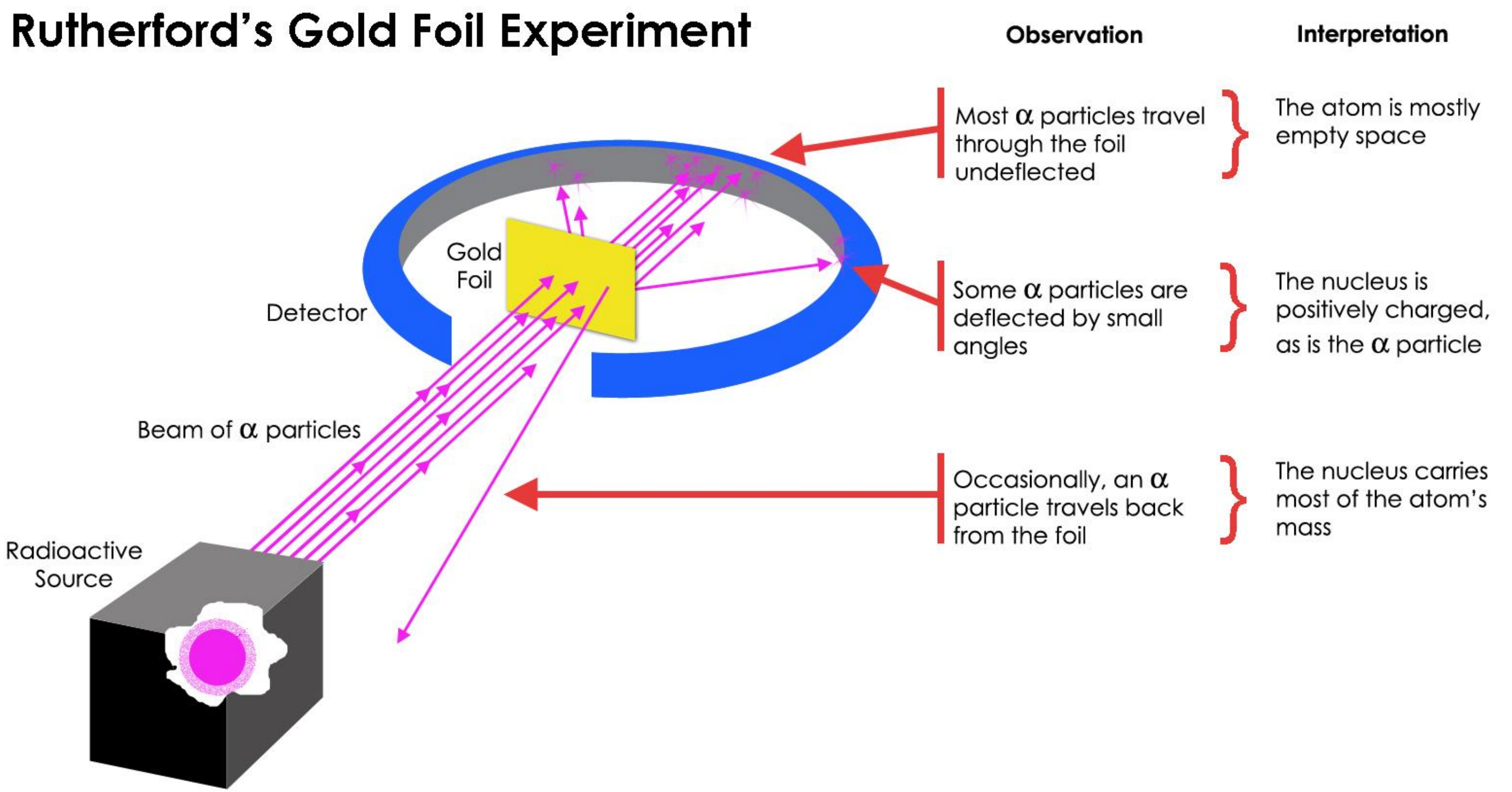

http://socratic.org/questions/what-were-the-aims-of-rutherford-experiment

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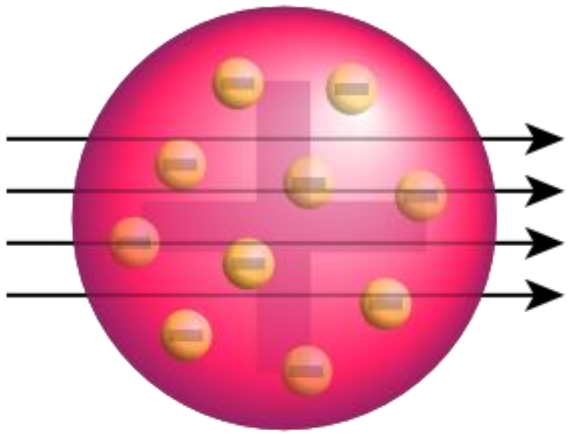

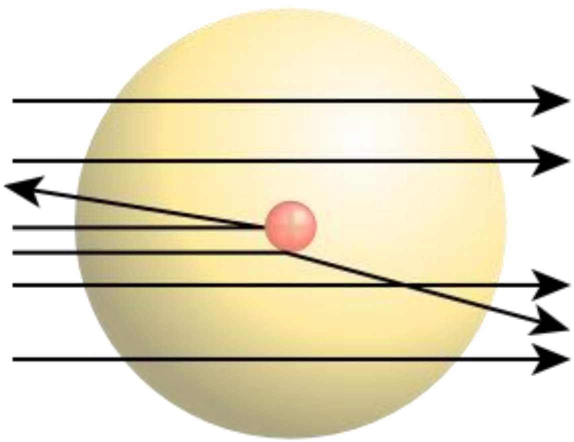

Sir Ernest Rutherford (1871 -1937)

Atoms	$\rightarrow 10^{-10}$ m
Nucleus	$\rightarrow 10^{-14}$ m
Proton, neutron	$\rightarrow 10^{-15}$ m

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Rutherford

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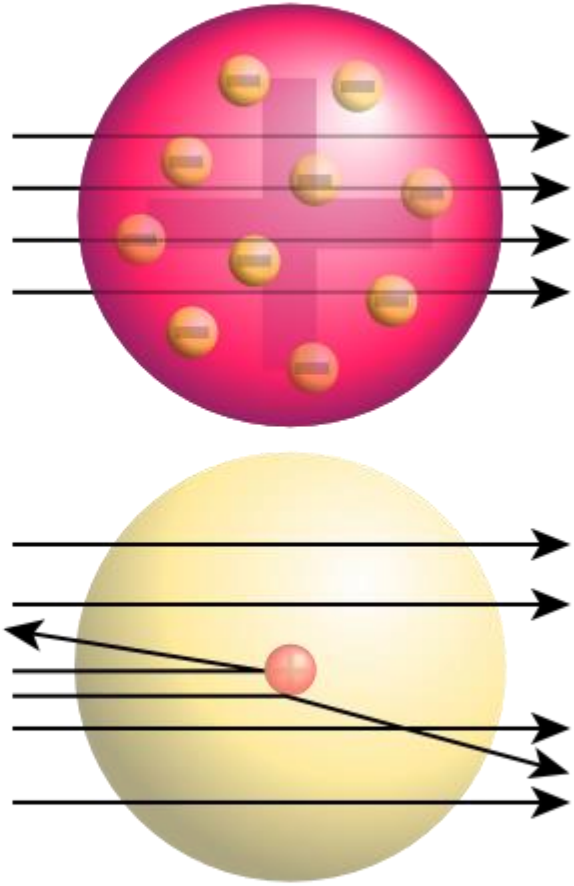

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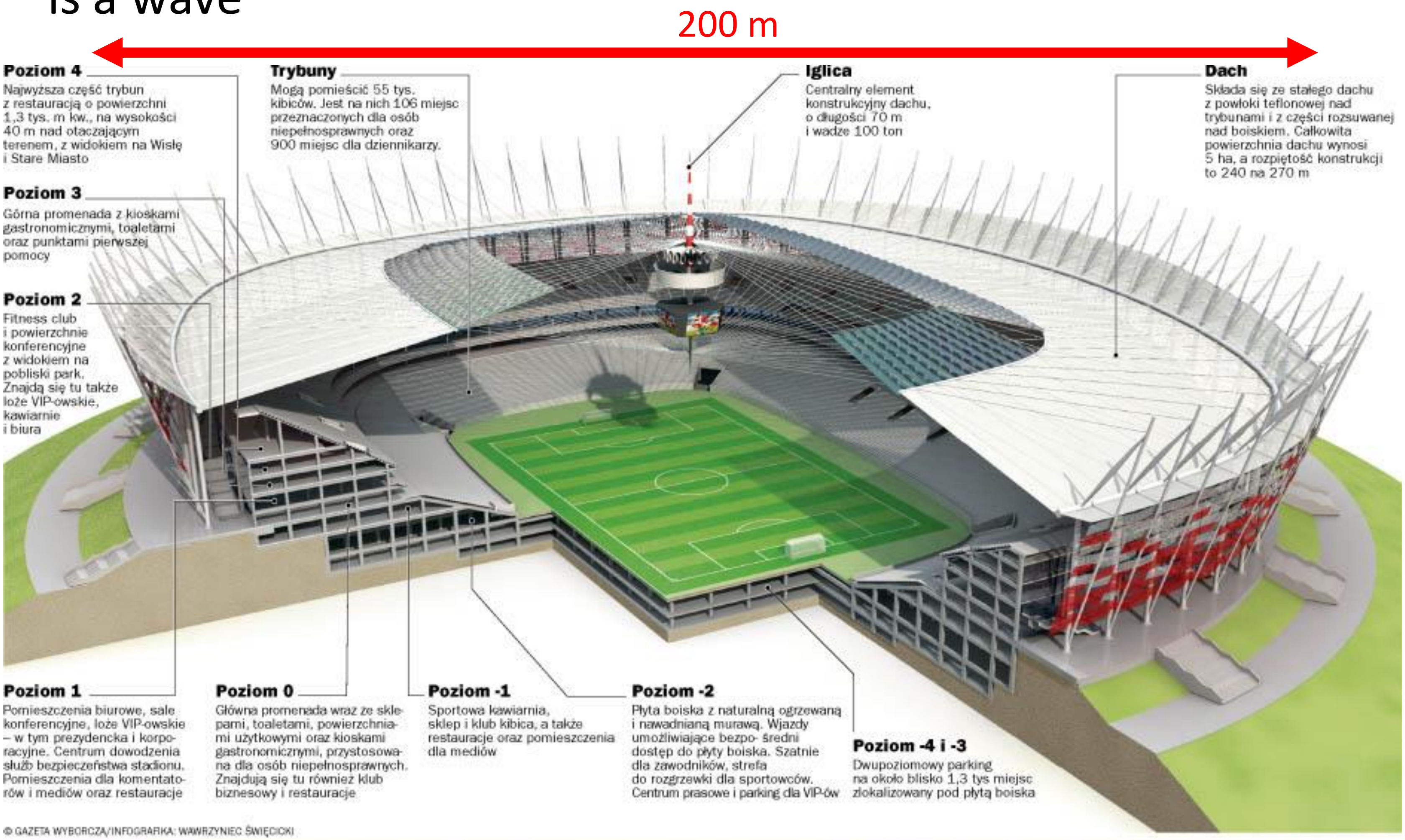

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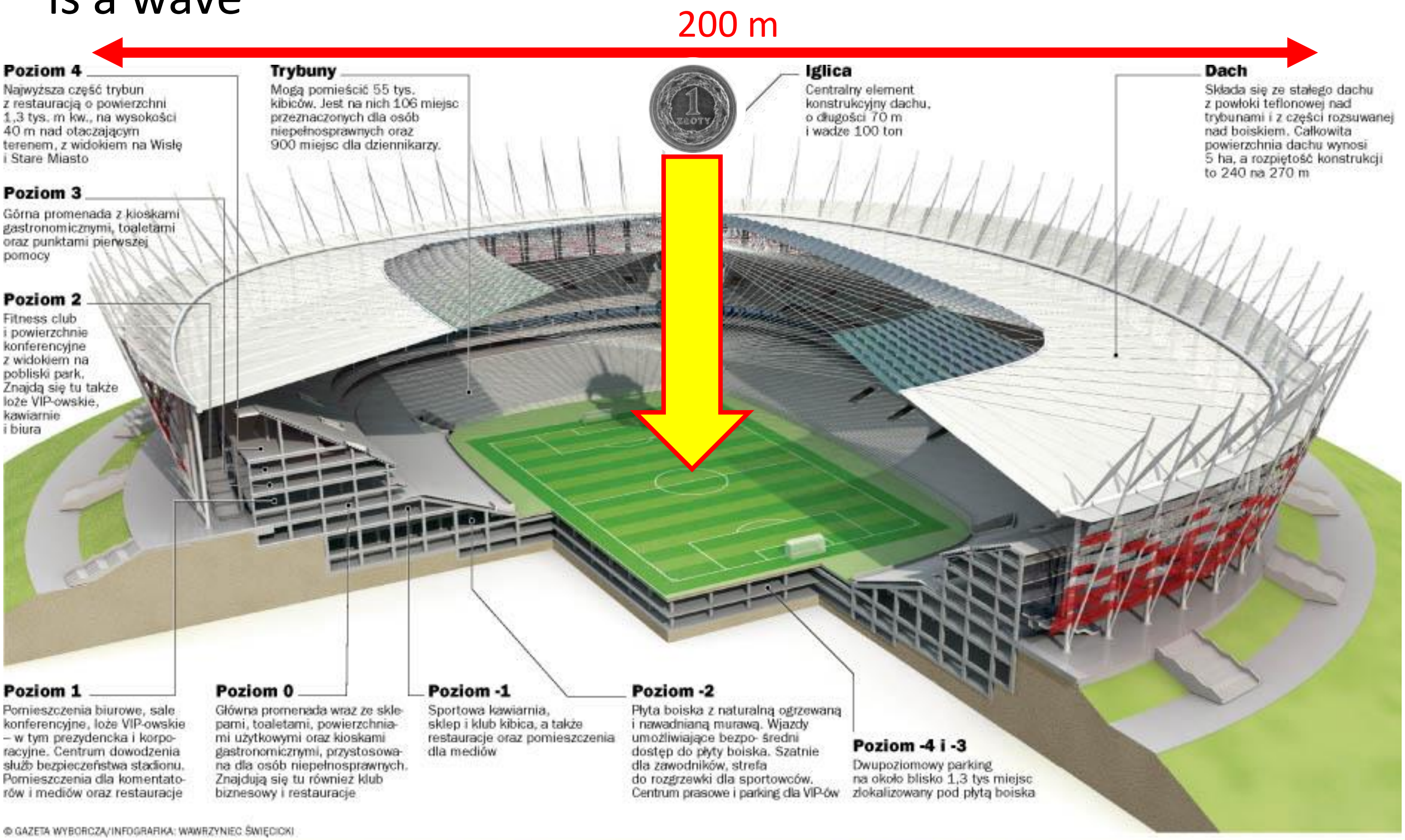

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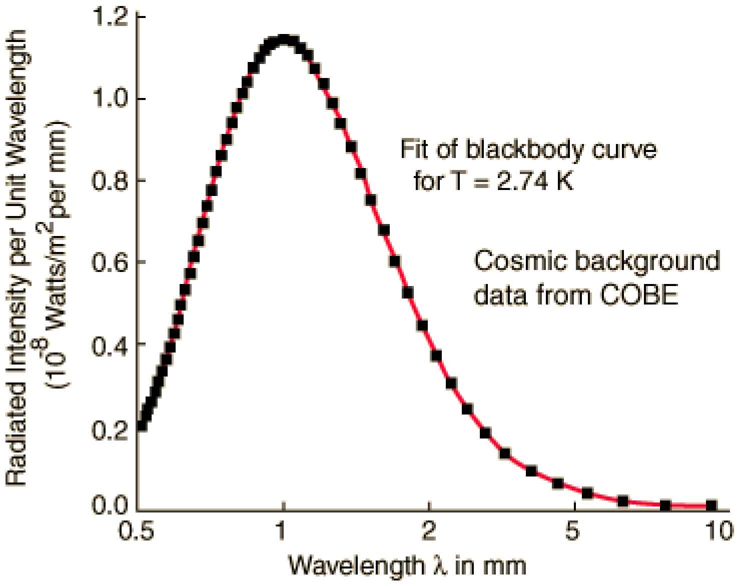
- In the XIX century: the matter is granular, the energy (mostly e-m) is a wave

- Problems NOT solved
  - Black body radiation
  - Photoelectric effect
  - Origin of spectral lines of atoms



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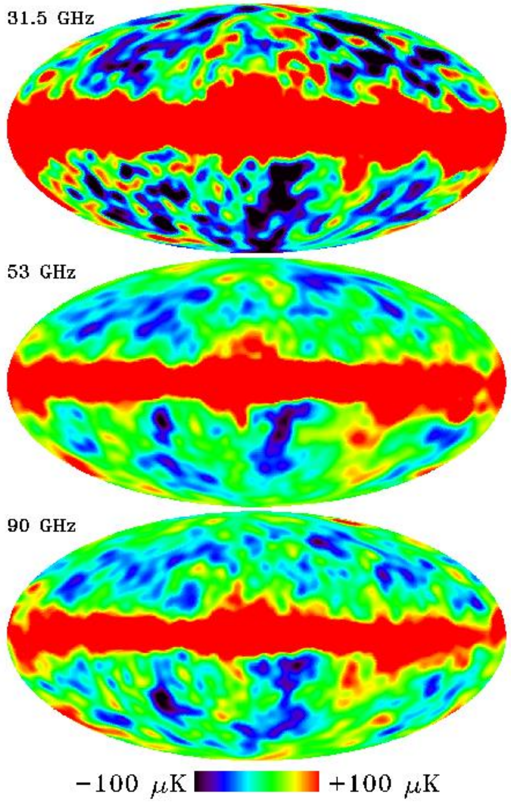


Materia i fale

The history

Albert Einstein, 5 Israeli Lirot (1968)

Erwin Schrödinger, 1000 Austrian Schilling (1983)

Niels Bohr, 500 Danish Kroner

Lord Ernest Rutherford, 100 New Zealand Dollars

http://www-personal.umich.edu/~jbourj/money1.htm

The history

- In the XIX century: the matter is granular, the energy (mostly e-m) is a wave
- In the XX century: the matter is (also) a wave and the energy is (also) granular (corpuscular)

The history

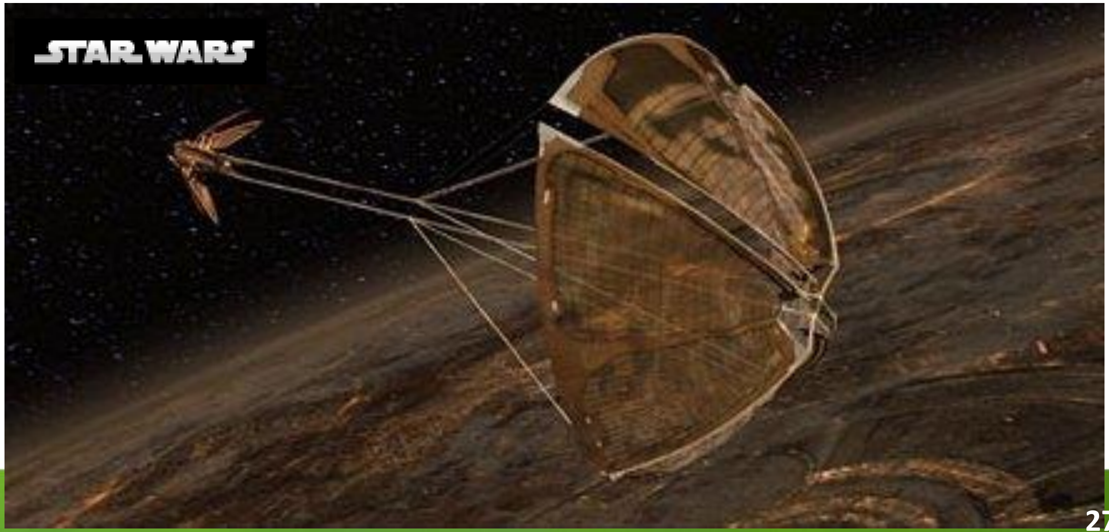
- In the XX century: the matter is (also) a wave and the energy is (also) granular (corpuscular)
- Solved problems:
  - Black body radiation spectrum (Planck 1900, Nobel 1918)
  - Photoelectric effect (Einstein 1905, Nobel 1922)
  - Origin of spectral lines of atoms (Bohr 1913, Nobel 1922)

$$\boxed{p = h / \lambda}$$

- *Photons* – *energy:* $E = h\nu$ (h = 6.626×10^{-32} J s = 4.136×10^{-15} eV s)

  – momentum: $p = E / c = h / \lambda$

Count Dooku's Geonosian solar sailer



light mill - **Crookes radiometer**

Trochę historii

In the XX century: the matter is (also) a wave and the energy is (also) granular (corpuscular)

Matter waves – De Broglie 1924 (Nobel 1929), experiments
G.P. Thomson L.H. Germer and C.J Davisson (Nobel 1937)

$$\lambda = h / p$$

$$p = h / \lambda$$

classically

http://www.colorado.edu/physics/2000/schroedinger/two-slit3.html

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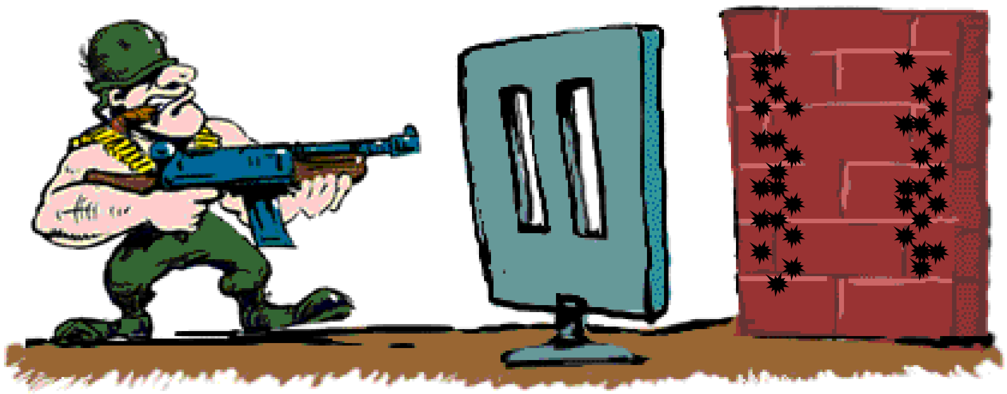
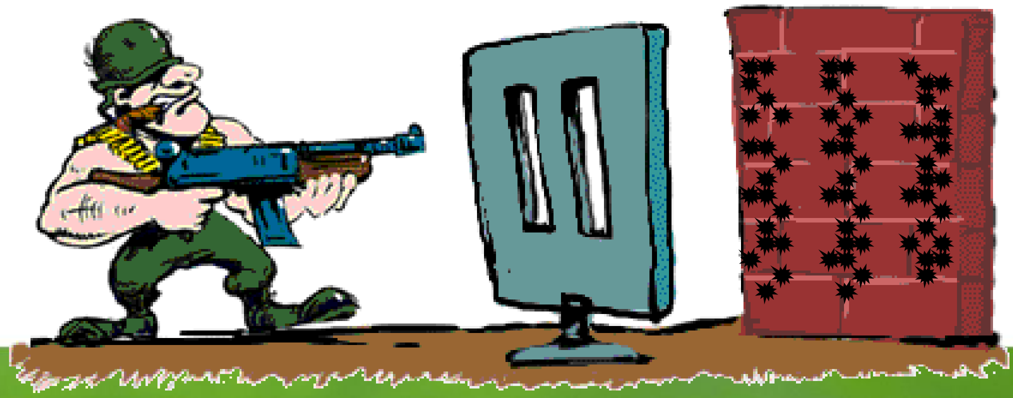


quantum



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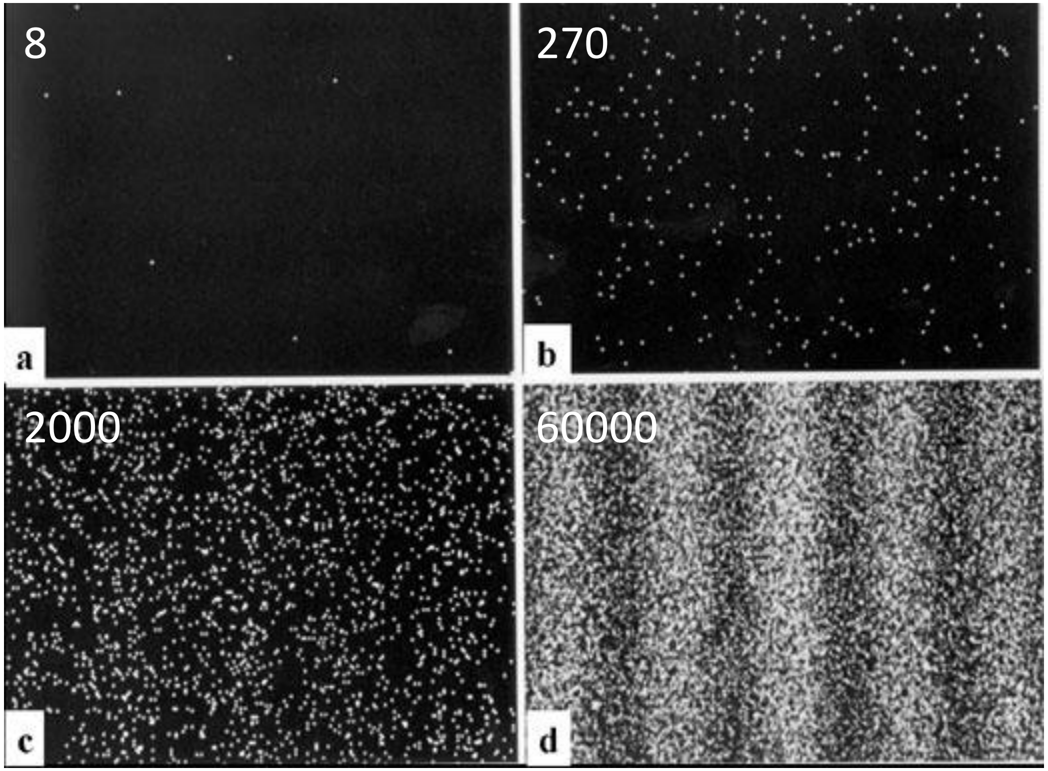

Single-electron events build up over a 20 minute exposure to form an interference pattern in this double-slit experiment by Akira Tonomura and co-workers. (a) 8 electrons; (b) 270 electrons; (c) 2000 electrons; (d) 60,000. A video of this experiment will soon be available on the web (www.hqrd.hitachi.co.jp/em/doubleslit.html).

www.hqrd.hitachi.co.jp

Trochę historii

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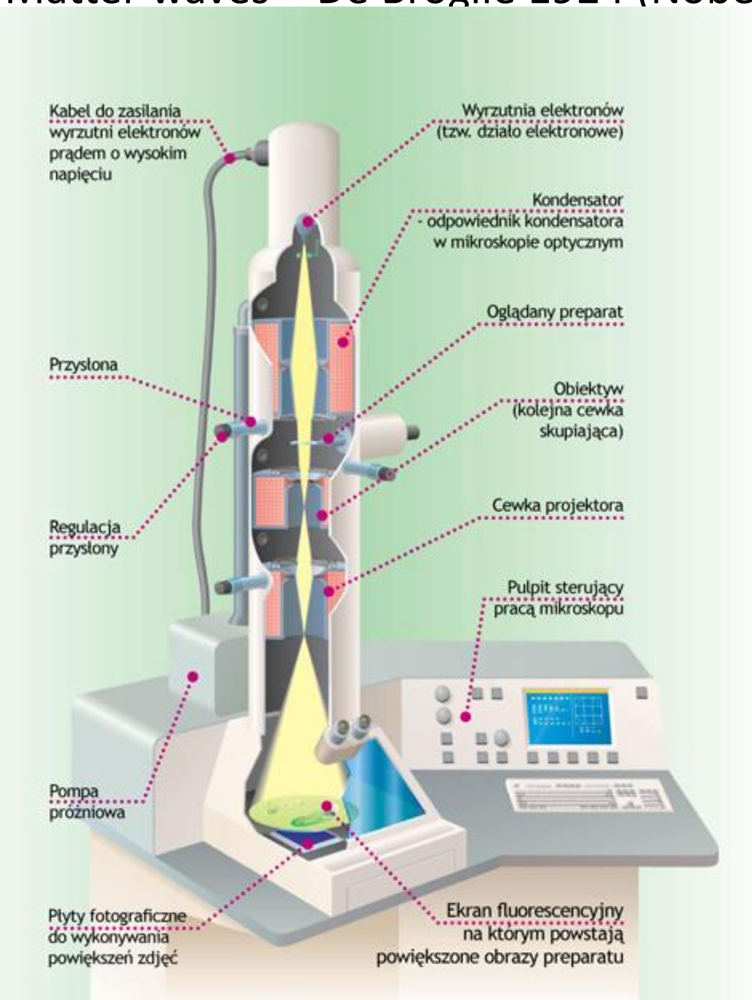
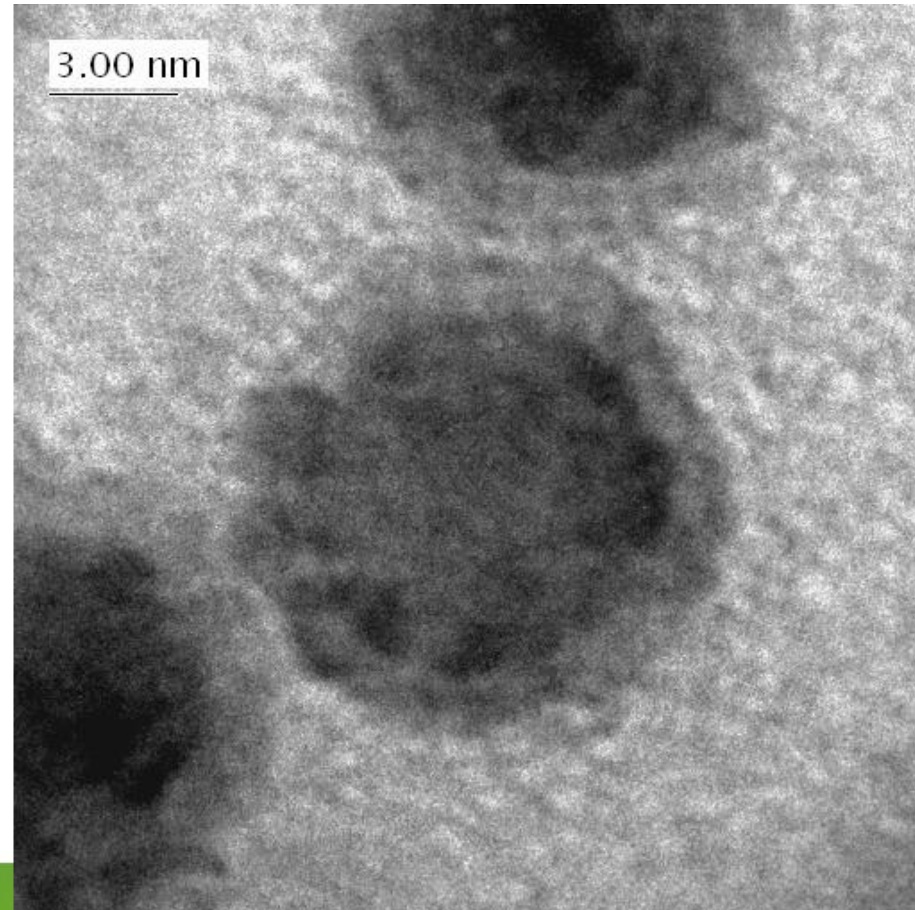
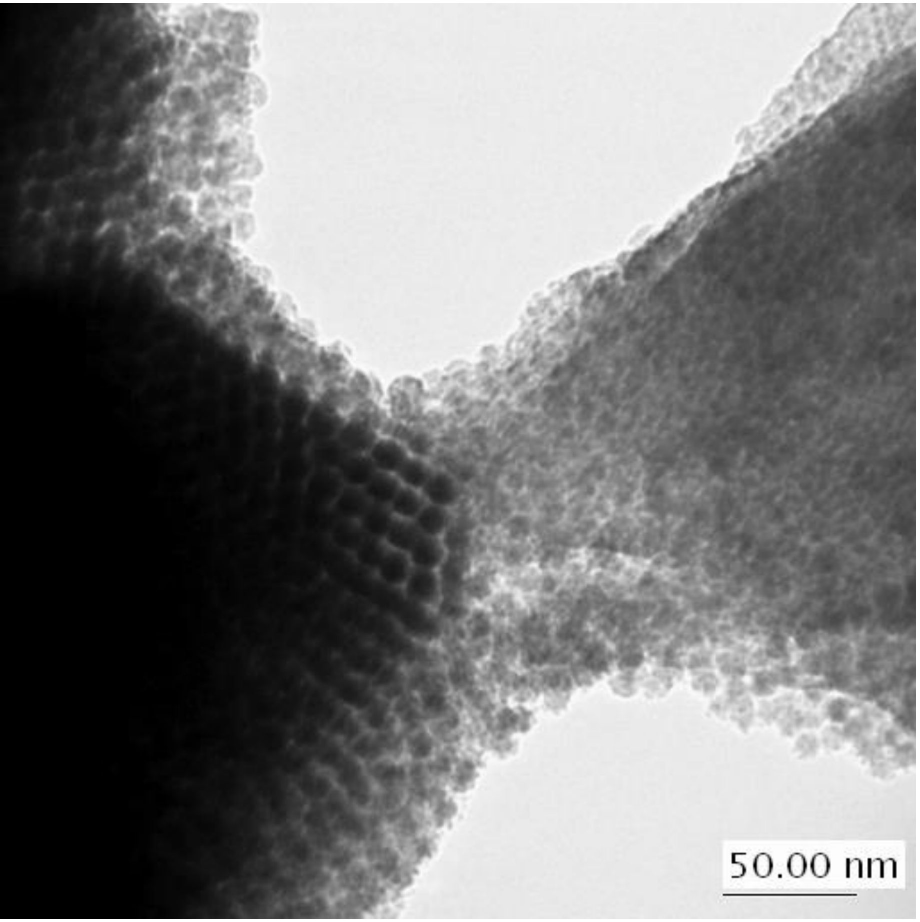
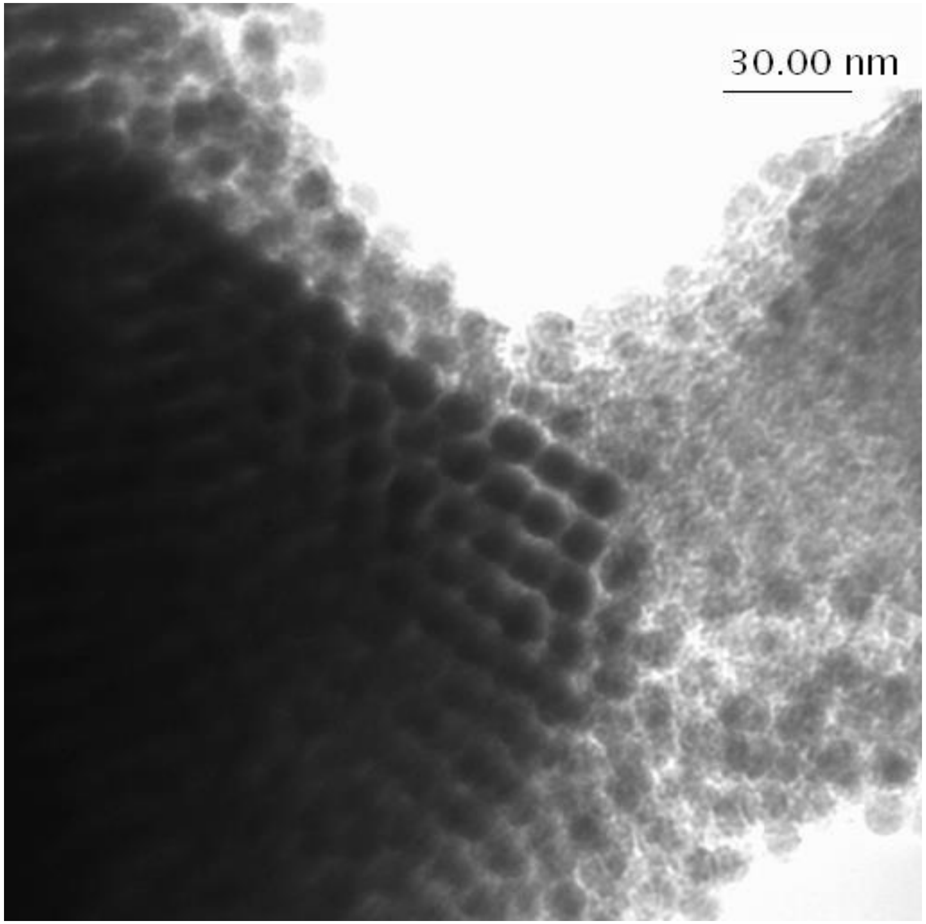




www.hqrd.hitachi.co.jp

Magnetic QDs





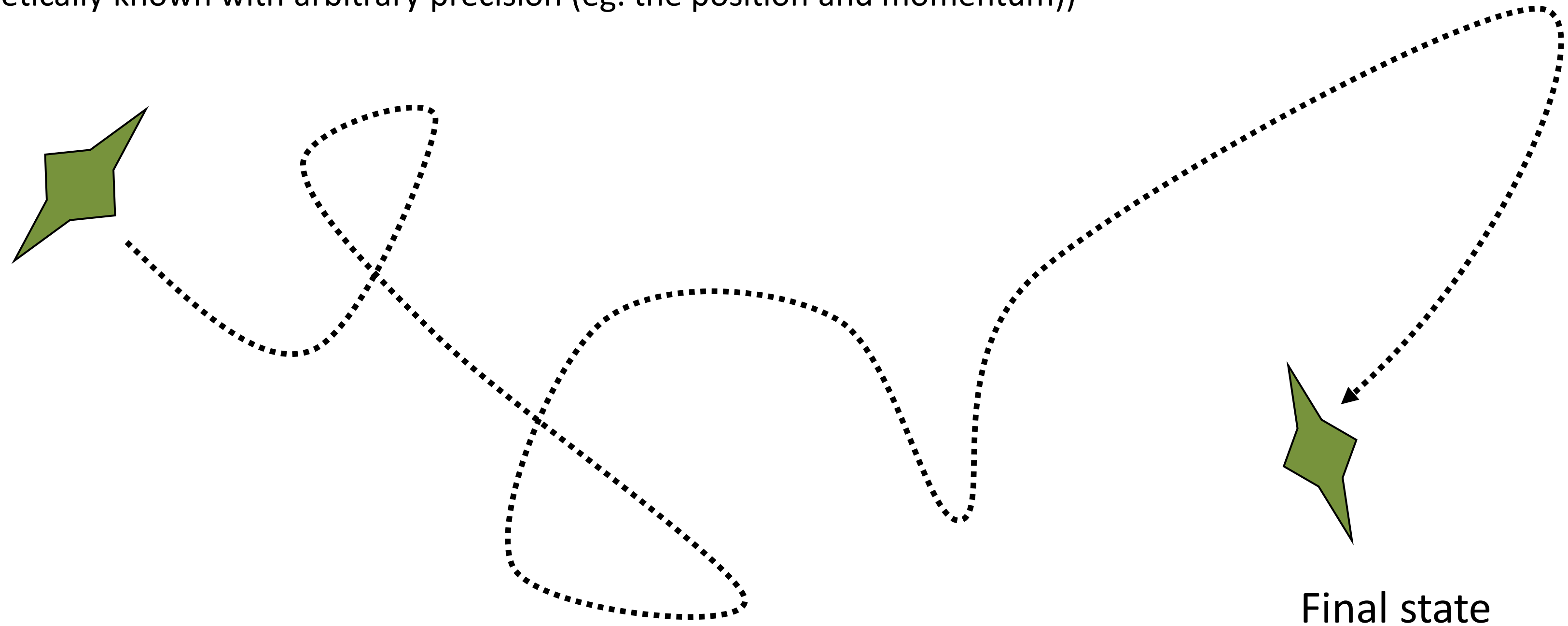
Synteza: Paweł Majewski, TEM: Jolanta Borysiuk

Dyfrakcja

Classical and quantum universe

Classical mechanics:

Initial conditions
(theoretically known with arbitrary precision (eg. the position and momentum))



Final state

Evolution (so-called. *state space*)
(Lagrange, Hamilton)

Classical and quantum universe

Classical mechanics:

Initial conditions

(theoretically known with arbitrary precision (eg. the position and momentum))

$$\vec{r}(t=0) = [x_0, y_0, z_0]$$

$$\vec{v} = [v_x, 0, v_z]$$

$$\vec{r}(t) = \left[x_0 + v_x t, y_0, z_0 + v_z t - \frac{gt^2}{2} \right]$$

Final state

Evolution (so-called. *state space*)

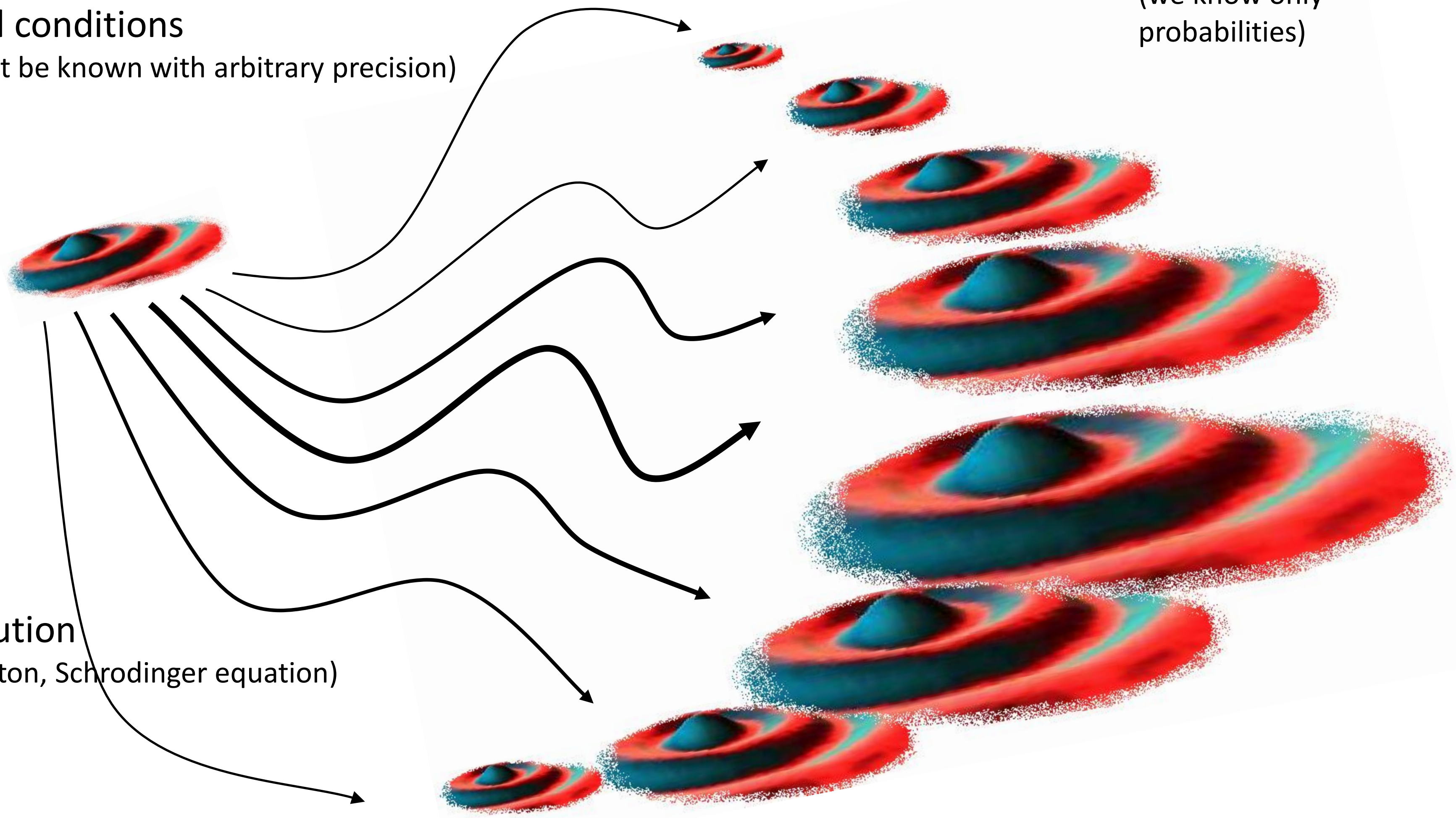
(Lagrange, Hamilton)

Classical and quantum universe

Quantum mechanics:

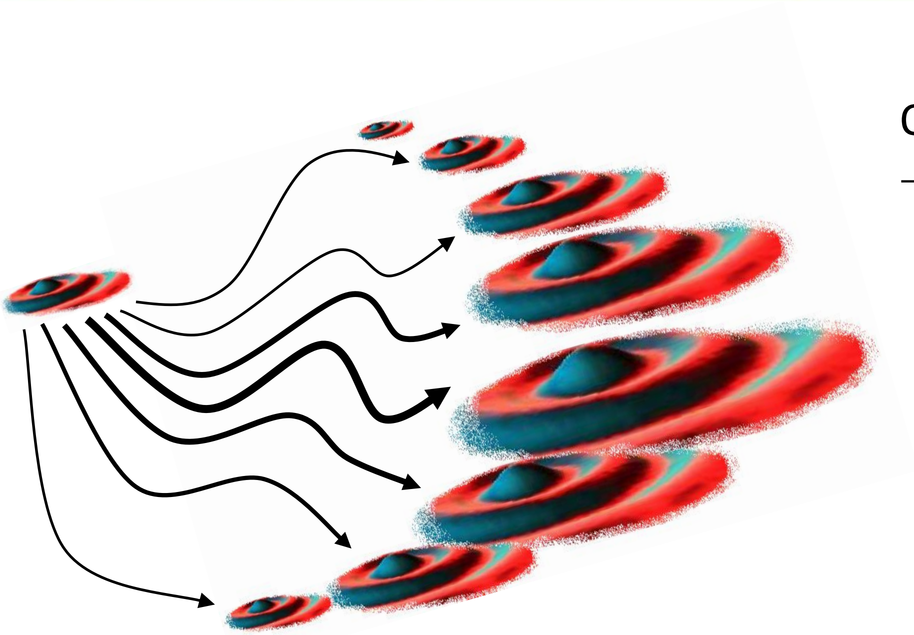
Initial conditions
(cannot be known with arbitrary precision)

Final states
(we know only probabilities)



Ewolution
(Hamilton, Schrodinger equation)

Classical and quantum universe



Quantum state must be defined in the whole space
$\rightarrow$ Wave function

$$\Psi_n(\vec{\boldsymbol{r}}, t)$$

n – quantum numbers

Remark 1: QUANTUM NUMBERS determine wave function:
Remark 2: the wave function is defined in the WHOLE SPACE, in that sense its evolution describes all of the possible trajectories (in space and time) of particles :
Remark 3: a LINEAR COMBINATION of wave functions is also a wave function (the principle of superposition)
Remark 4: evolution of the wave function is DETERMINISTIC. However, by measurement a superposition of several eigenstates reduces to a single eigenstate (*wave function collapse*)
Remark 5: quantum particles are INDISTINGUISHABLE

Vector space of wave functions (Hilbert space), operators, eigen states and eigen functions, etc.

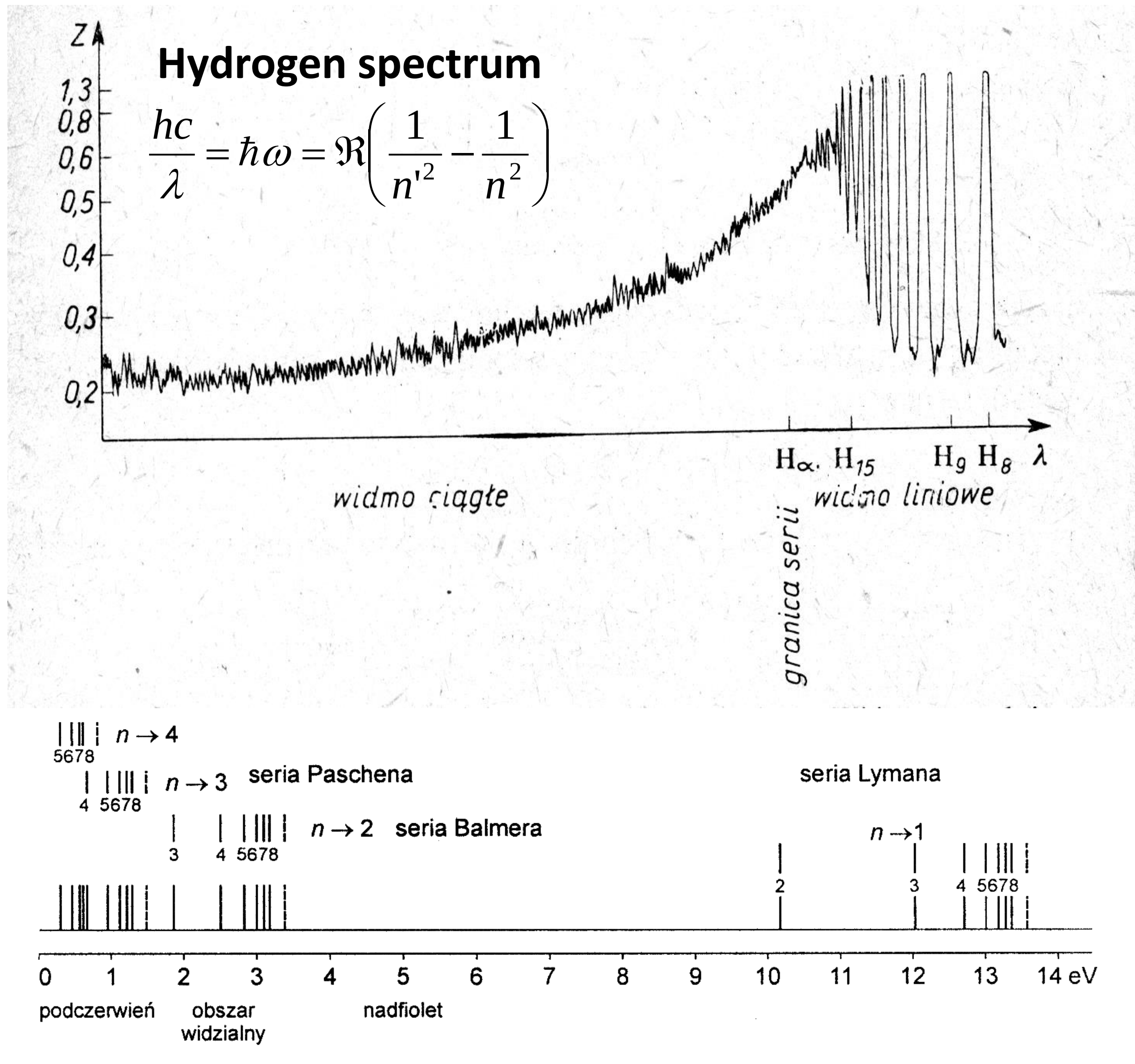
<u>Remark 1</u>: QUANTUM NUMBERS determine wave function::

$$\Psi_n(\vec{\mathbf{r}}, t)$$

n – quantum numbers

<u>Exaples of„quantum”</u>

mass, charge, energy ("energy levels" in an atom in the crystal), momentum (orbital, spin), the projection of angular momentum, minimum light intensity of the energy ***E = h*** ν, polarization of light, etc ..

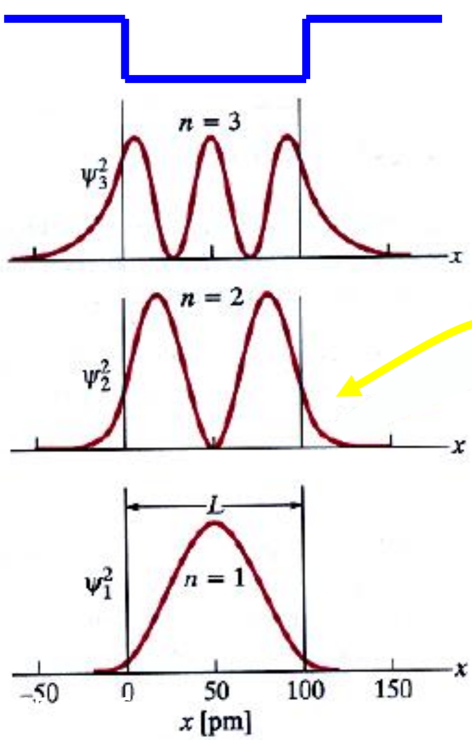


Classical and quantum universe

<u>Remark 2</u>: the wave function is defined in the WHOLE SPACE, in that sense its evolution describes all of the possible trajectories (in space and time) of particles :

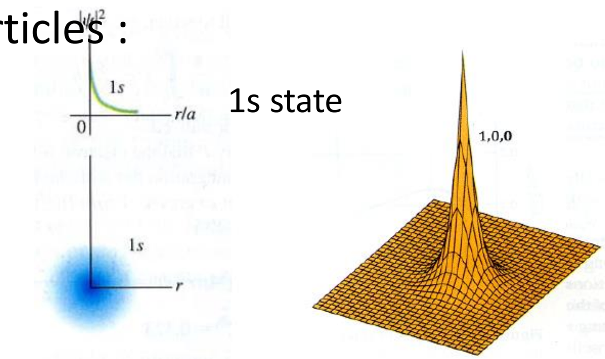
$$\left|\Psi_n(\vec{\mathbf{r}}, t)\right|^2 \textit{ probability density}$$

$$\hat{H}\,\Psi(\vec{r}) = \left[E_{kin}(\vec{p}) + E_{pot}(\vec{r})\right]\Psi(\vec{r}) = E\,\Psi(\vec{r})$$

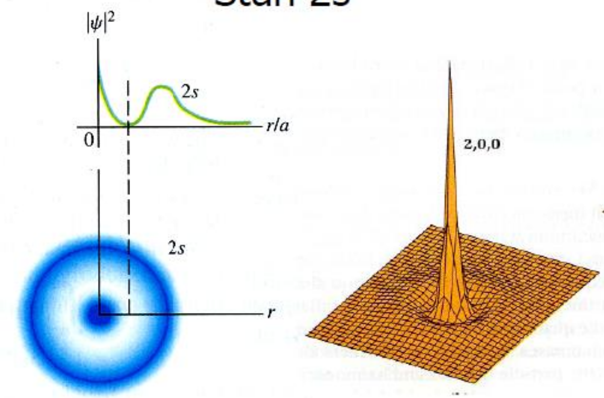


Trapped particle penetrates the potential barrier

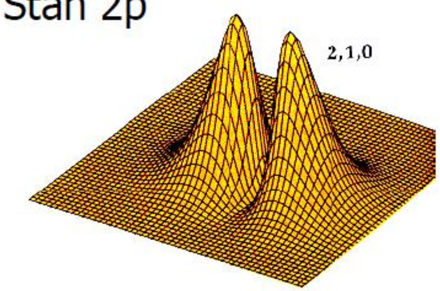
1s state



Stan 2s



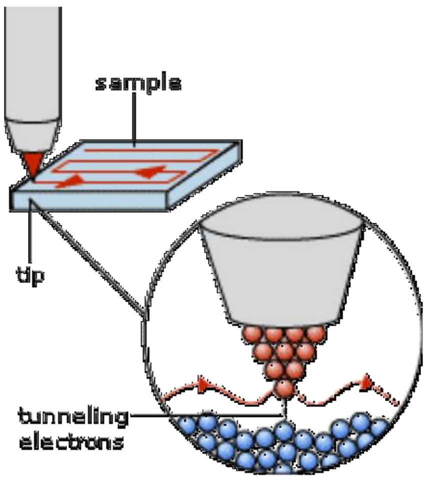
Stan 2p

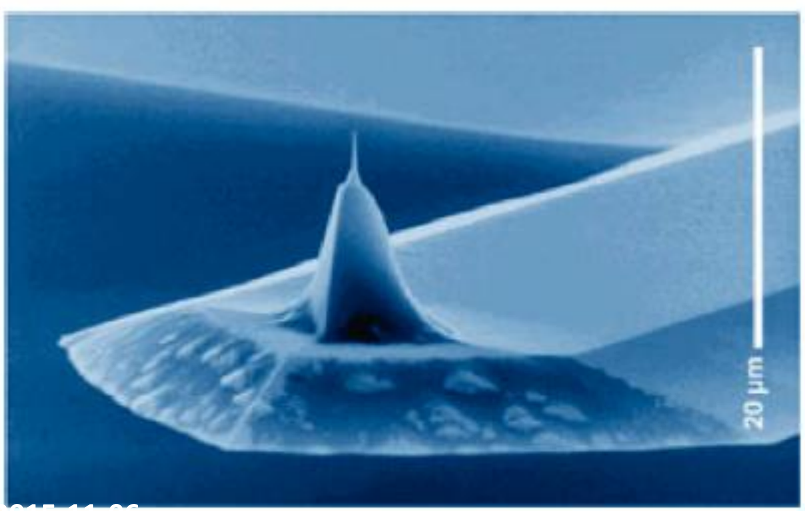


Classical and quantum universe

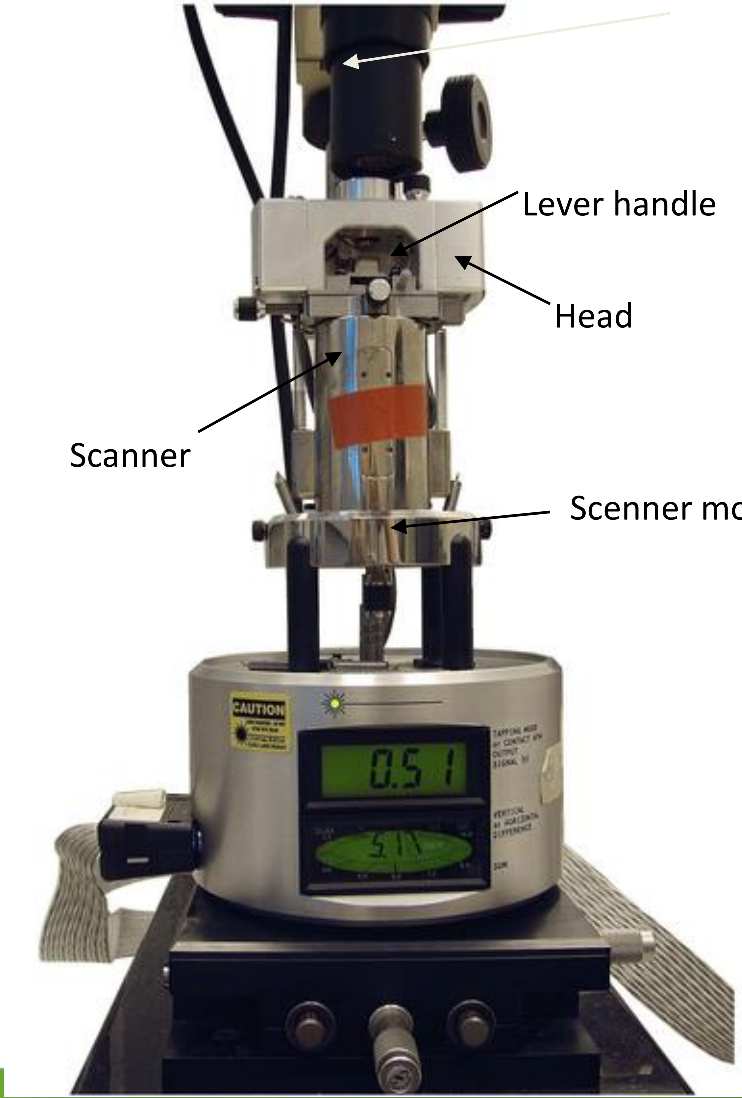
STM – Scanning Tunnelling Microscope

Nobel 1986 Gerd Binnig, Heinrich Rohrer



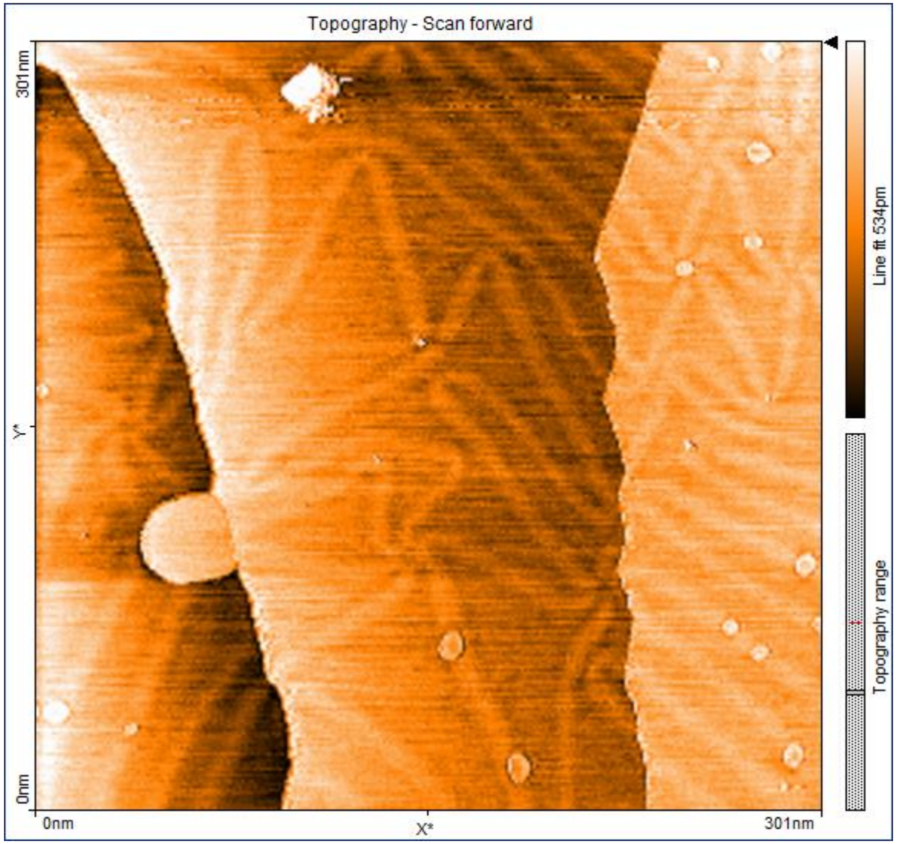


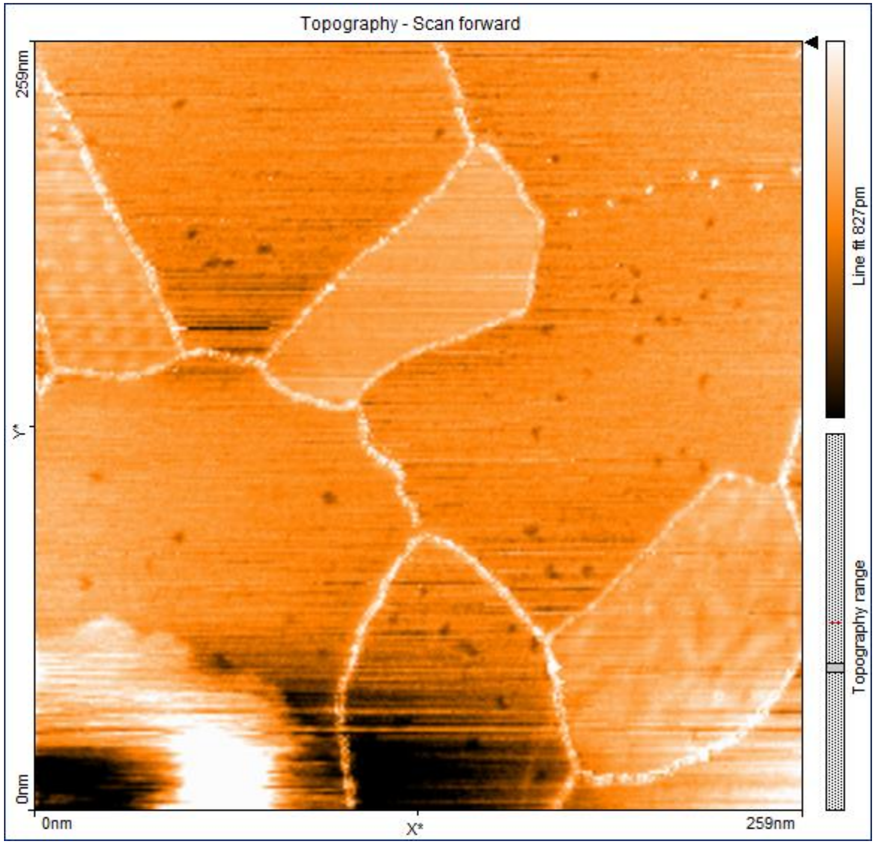
www.nanosensors.com



Classical and quantum universe

Polish graphene





Iskry

Classical and quantum universe

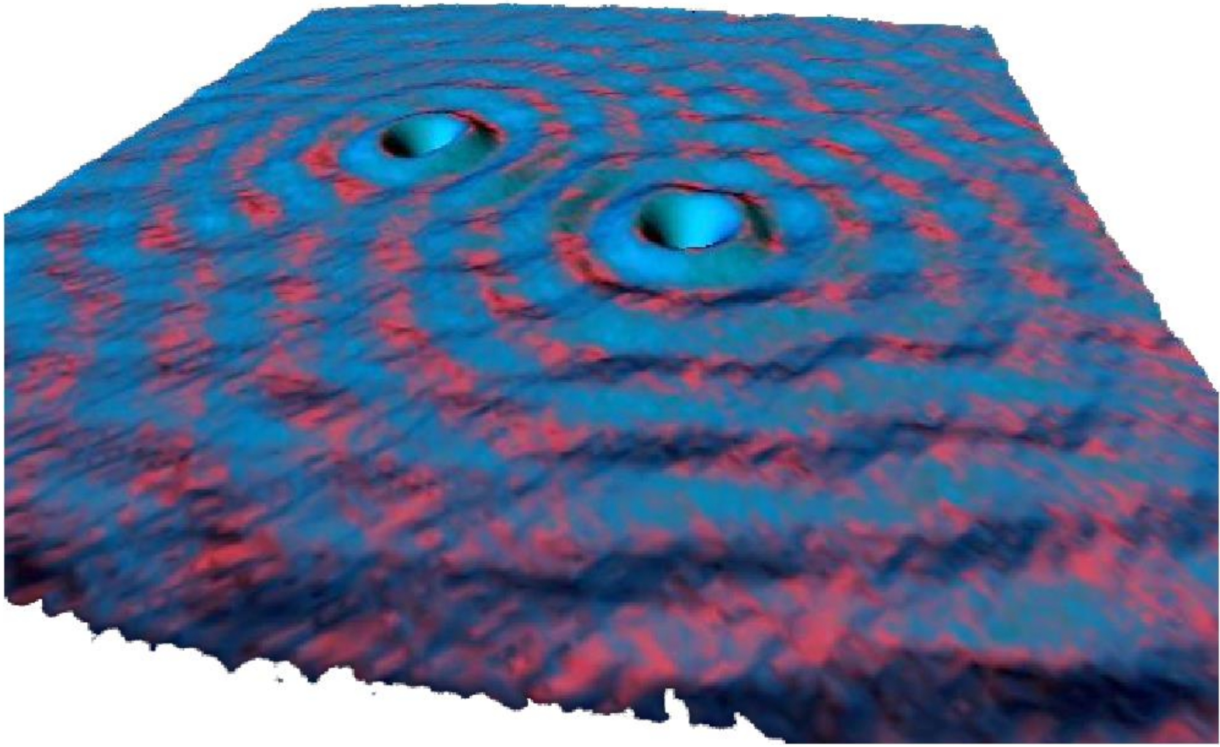
Remark 3: a LINEAR COMBINATION of wave functions is also a wave function (the principle of superposition)

$$\Psi = A\Psi_A + B\Psi_B$$

$$\cancel{|\Psi|^2 \neq A^2|\Psi_A|^2 + B^2|\Psi_B|^2}$$

$$|\Psi|^2 = A^2|\Psi_A|^2 + B^2|\Psi_B|^2 \boxed{+2AB\Psi_A\Psi_B}$$

interference term



A quantum waves

In this scanning tunneling microscope (STM) image, electron density waves are seen to be breaking around two atom-sized defects on the surface of a copper crystal. The resultant standing waves result from the interference of the electron waves scattering from the defects. Courtesy, Don Eigler, IBM.

Classical and quantum universe

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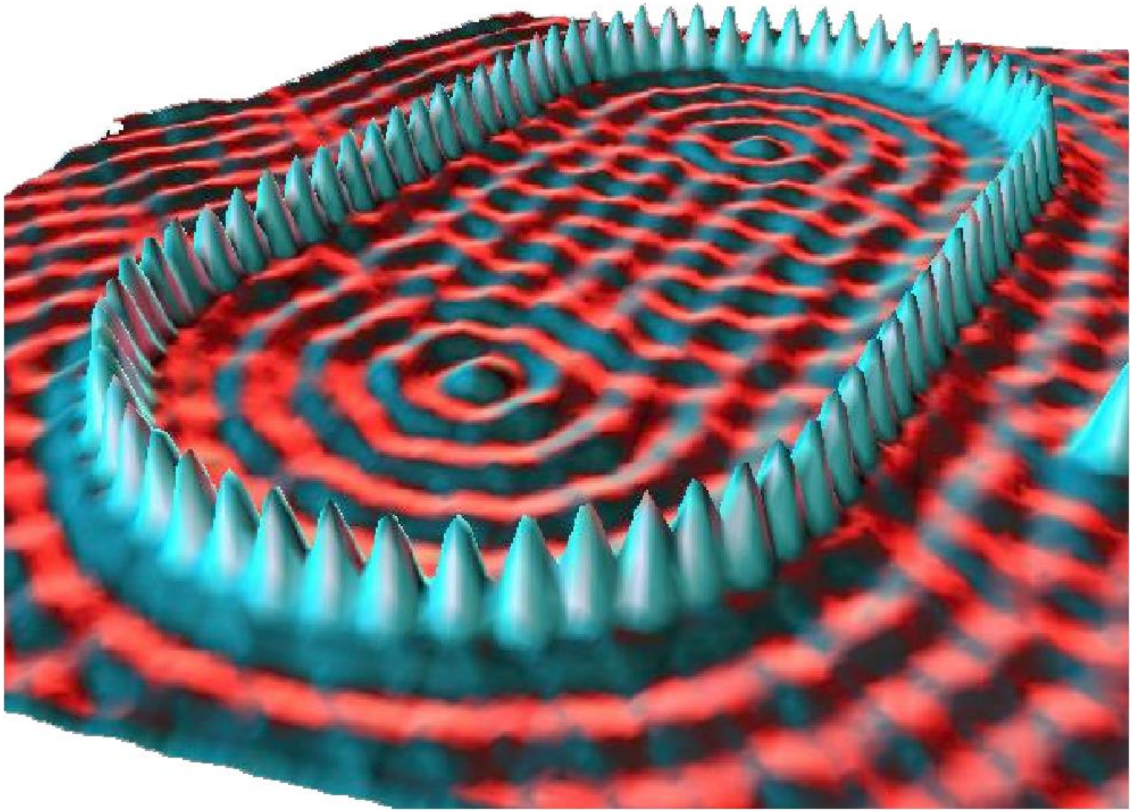
interference term

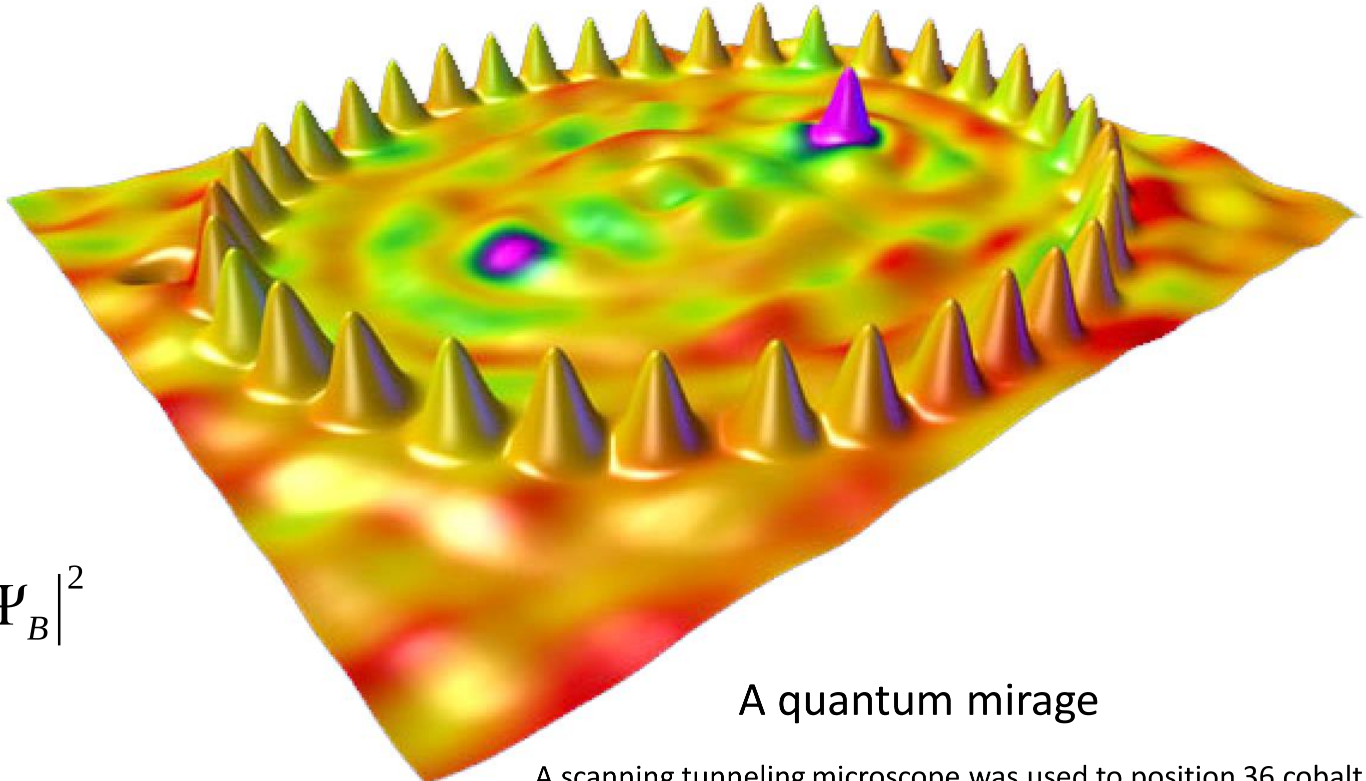


A quantum corral

Scanning tunnelling microscope (STM) picture of a stadium-shaped "quantum corral" made by positioning iron atoms on a copper surface. This structure was designed for studying what happens when surface electron waves in a confined region. Courtesy, Don Eigler, IBM.

Classical and quantum universe

Remark 3: a LINEAR COMBINATION of wave functions is also a wave function (the principle of superposition)



$$\Psi = A\Psi_A + B\Psi_B$$

$$\cancel{|\Psi|^2 \neq A^2|\Psi_A|^2 + B^2|\Psi_B|^2}$$

$$|\Psi|^2 = A^2|\Psi_A|^2 + B^2|\Psi_B|^2 + 2AB\Psi_A\Psi_B$$

interference term

A quantum mirage

A scanning tunneling microscope was used to position 36 cobalt atoms in an elliptical structure known as a "quantum corral." Electron waves moving in the copper substrate interact both with a magnetic cobalt atom carefully positioned at one of the foci of the ellipse and apparently with a "mirage" of another cobalt atom (that isn't really there) at the other focus. (Courtesy of IBM.) reported by: Manoharan et al., in [Nature](), 3 February 2000

Interferencja

Classical and quantum universe

<u>Remark 4</u>: evolution of the wave function is DETERMINISTIC. However, by measurement a superposition of several eigenstates reduces to a single eigenstate (*wave function collapse*)

"About your cat, Mr. Schrödinger—I have good news and bad news."

Świat klasyczny i kwantowy

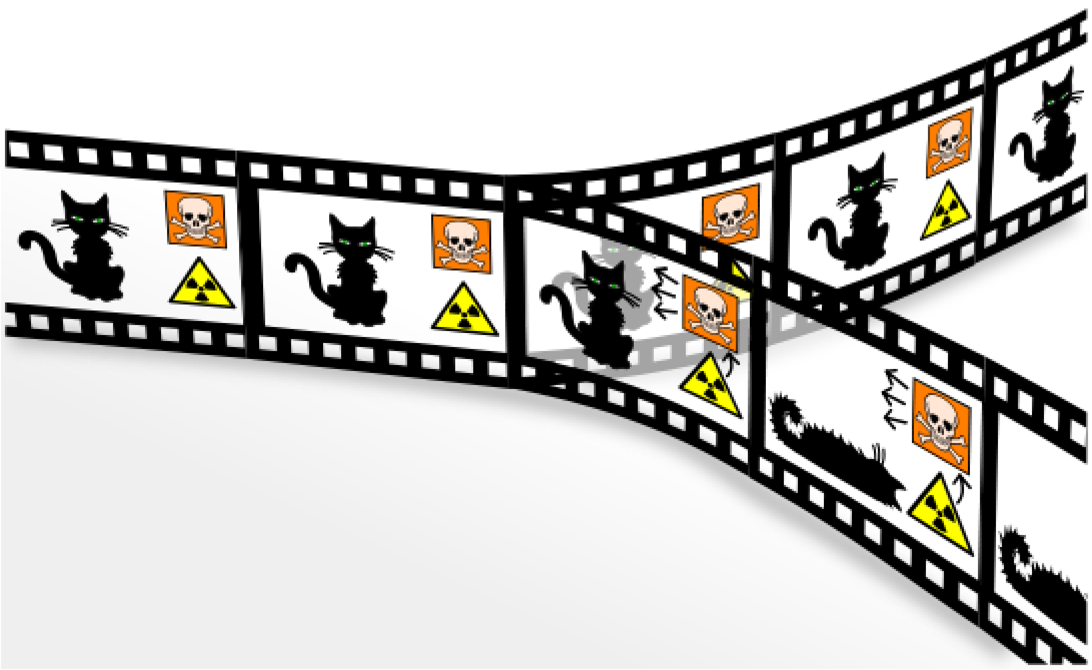
<u>Remark 4</u>: evolution of the wave function is DETERMINISTIC. However, by measurement a superposition of several eigenstates reduces to a single eigenstate (*wave function collapse*)

measurements

$\boldsymbol{A}$ lub $\boldsymbol{B}$

$$\Psi = A\Psi_A + B\Psi_B \longrightarrow \begin{cases} \Psi = \Psi_A \longrightarrow \Psi = \Psi_A \\ \Psi = \Psi_B \longrightarrow \Psi = \Psi_B \end{cases}$$

Probability $\boldsymbol{A^2}$ or $\boldsymbol{B^2}$



Classical and quantum universe

<u>Remark 4</u>: evolution of the wave function is DETERMINISTIC. However, by measurement a superposition of several eigenstates reduces to a single eigenstate (*wave function collapse*)

measurements

A lub **B**

$$\Psi = A\Psi_A + B\Psi_B$$

$$\Psi = \Psi_A \longrightarrow \Psi = \Psi_A$$

$$\Psi = \Psi_B \longrightarrow \Psi = \Psi_B$$

Probability A^2 or B^2

Sometimes the ORDER of a measurement is important <u>:</u>

$$[\hat{p}, \hat{x}] = -i\hbar$$

measurement = observables= operators= commutation rules

Heisenberg's uncertainty principle (position and momentum, energy and time, projections of momentum and momentum, etc.).

$$\Delta p \Delta x \geq \frac{1}{2}\hbar$$

$$\hat{U}\hat{W}\,\Psi \neq \hat{W}\hat{U}\,\Psi \quad \text{gdy} \quad \hat{U}\hat{W} - \hat{W}\hat{U} = [\hat{U}, \hat{W}] \neq 0$$

<u>Superposition of states, entanglement</u>

Synthesis of quantum dots

Heisenberg's uncertainty principle

CdSe/ZnS 1-10 nm http://www.nanopicoftheday.org/2003Pics/QDRainbow.htm

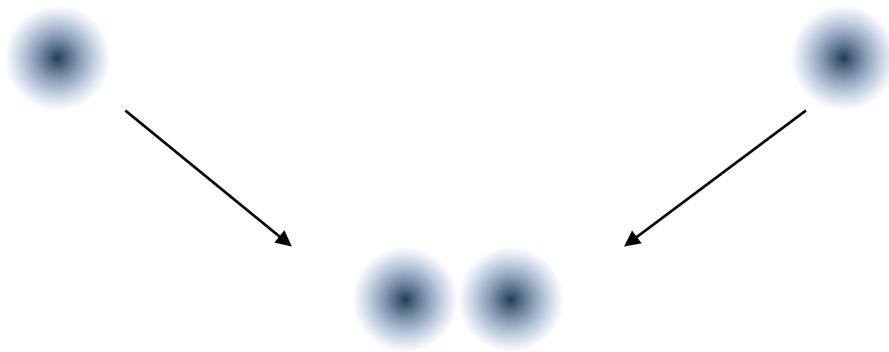
3 polaryzatory

Classical and quantum universe

Remark 5: quantum particles are INDISTINGUISHABLE

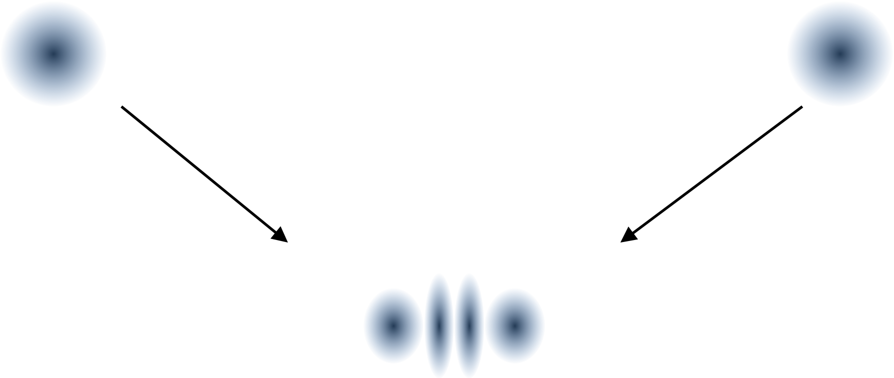
Classical and quantum universe

<u>Remark 5</u>: quantum particles are INDISTINGUISHABLE



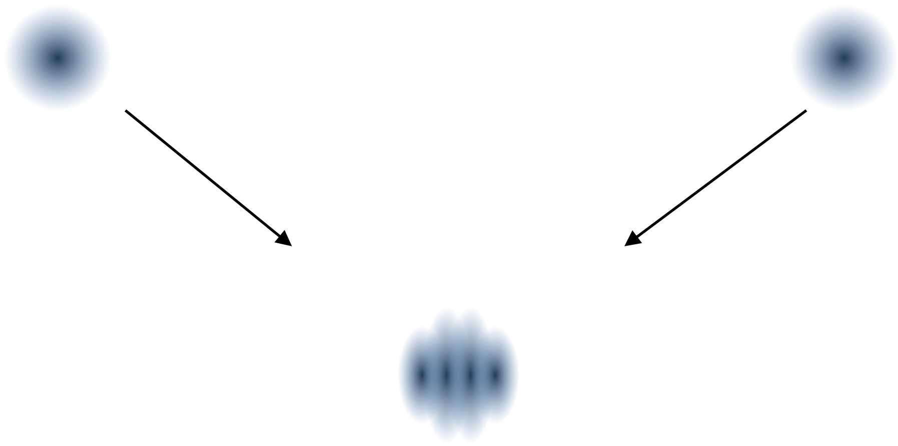
Classical and quantum universe

Remark 5: quantum particles are INDISTINGUISHABLE



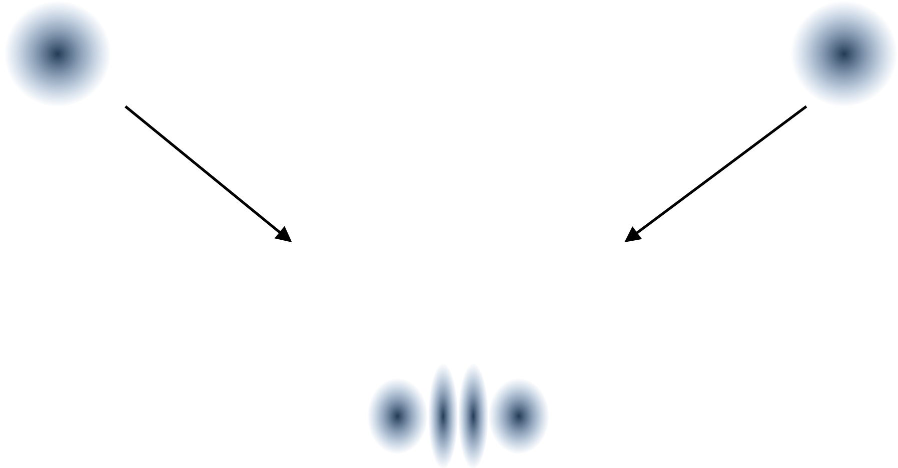
Classical and quantum universe

Remark 5: quantum particles are INDISTINGUISHABLE



Classical and quantum universe

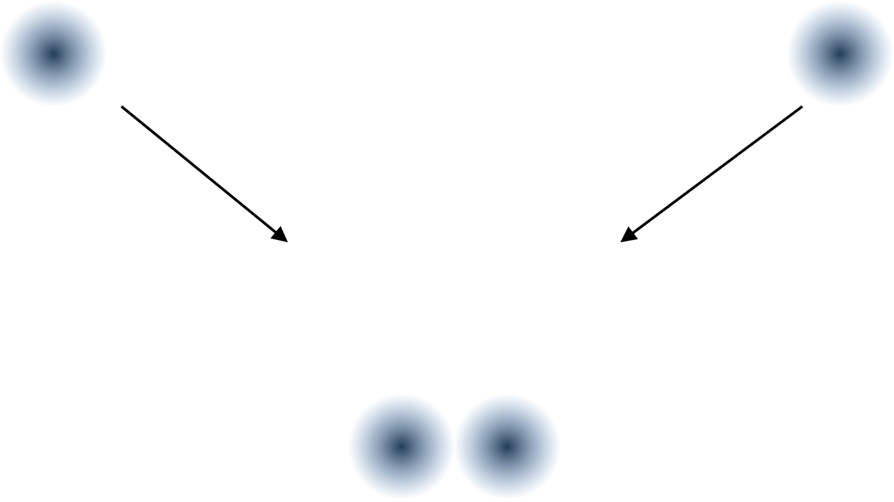
Remark 5: quantum particles are INDISTINGUISHABLE



2015-11-06

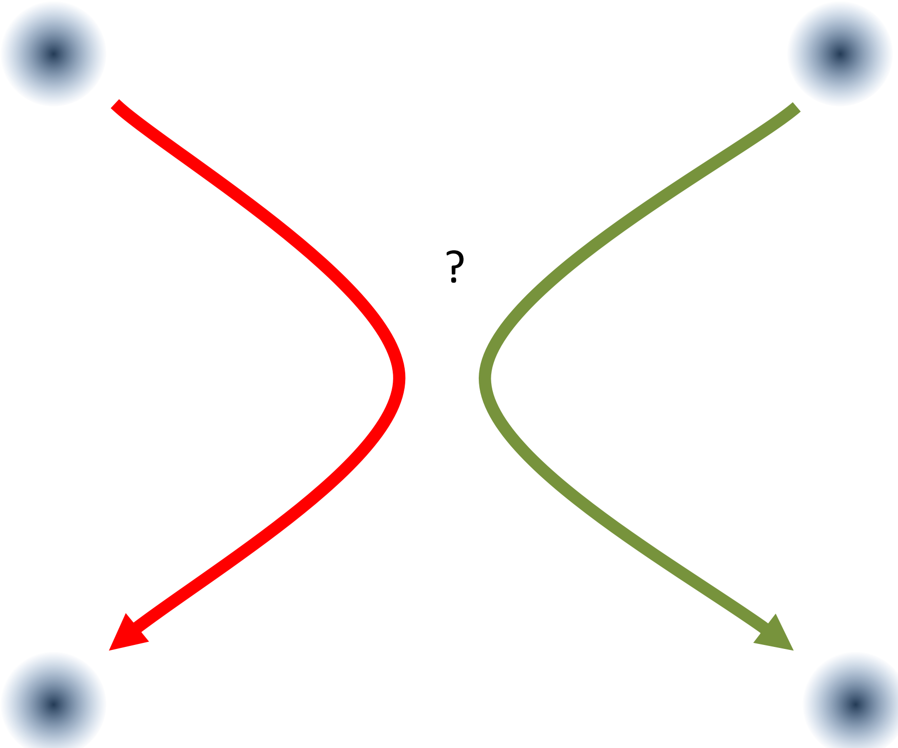
Classical and quantum universe

<u>Remark 5</u>: quantum particles are INDISTINGUISHABLE



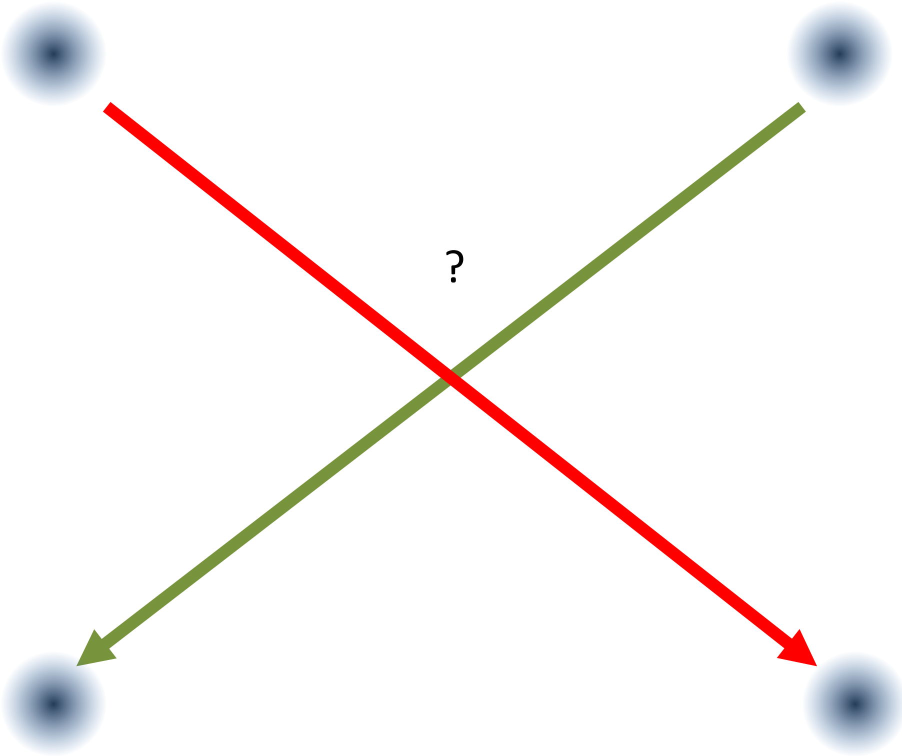
Classical and quantum universe

<u>Remark 5</u>: quantum particles are INDISTINGUISHABLE



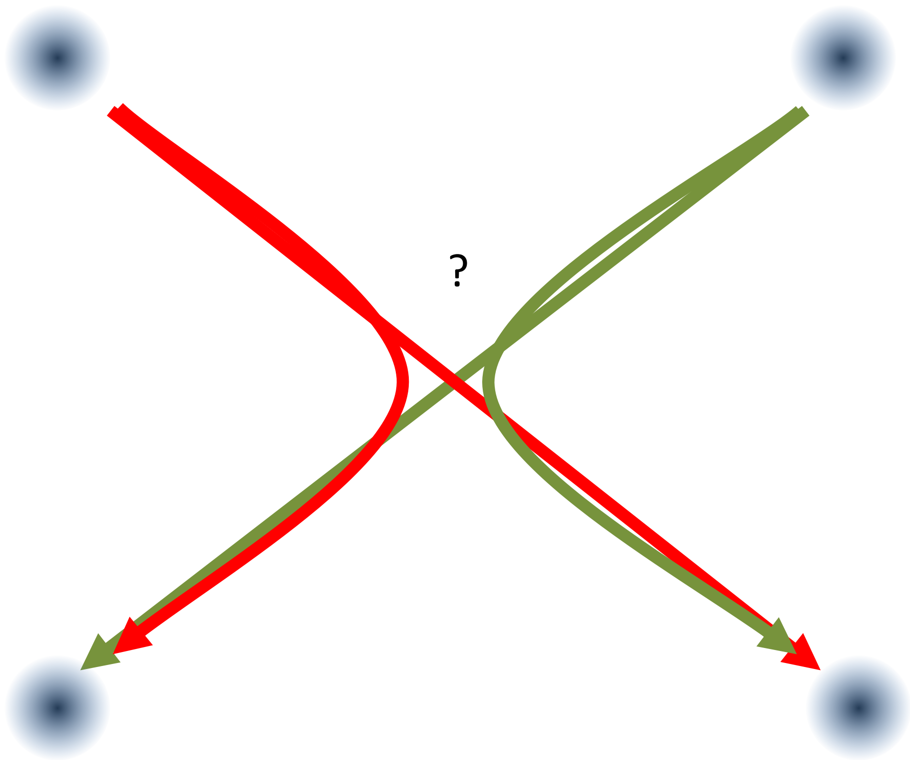
Classical and quantum universe

Remark 5: quantum particles are INDISTINGUISHABLE



Classical and quantum universe

Remark 5: quantum particles are INDISTINGUISHABLE



The wave function of the whole system
STATISTICS:

World fermions (e, p, n)
World bosons (photon, W boson)

Pauli exclusion principle, Fermi-Dirac statistics, Bose-Einstein; exchange interaction, ferromagnetism

Nadprzewodnik

Conclusions (certain)

The mathematical description by ***eigenstates*** (*orthogonal*) $\{|A\rangle, |B\rangle\}$

Two atomic levels $\{|g\rangle, |e\rangle\}$ np. $g = 1s$, $e = 2s$

Electron spin $\{|\uparrow\rangle, |\downarrow\rangle\}$ $\{|\circlearrowleft\rangle, |\circlearrowright\rangle\}$

Photon of two mutually orthogonal polarization states $\{|\rightarrow\rangle, |\uparrow\rangle\}$

If the state of the particles describes two states A and B (superposition of states), the particle cannot be observed in both of them at the same time (so-called. orthogonality of states)!

$$\boxed{\Psi = A\Psi_A + B\Psi_B}$$

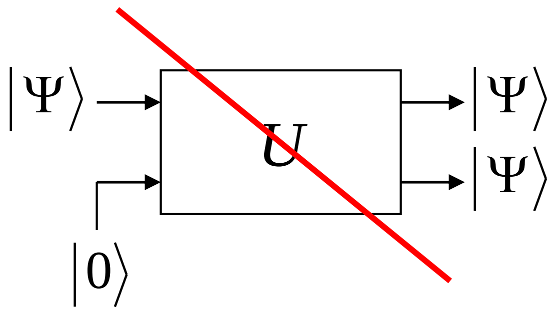
$$\Psi = A\Psi_A + B\Psi_B \xrightarrow{\text{evolution}} \begin{cases} \Psi = \Psi_A \longrightarrow \Psi = \Psi_A \\ \Psi = \Psi_B \longrightarrow \Psi = \Psi_B \end{cases}$$

measurement ***A*** or ***B***
probability A^2 or B^2

No cloning theorem

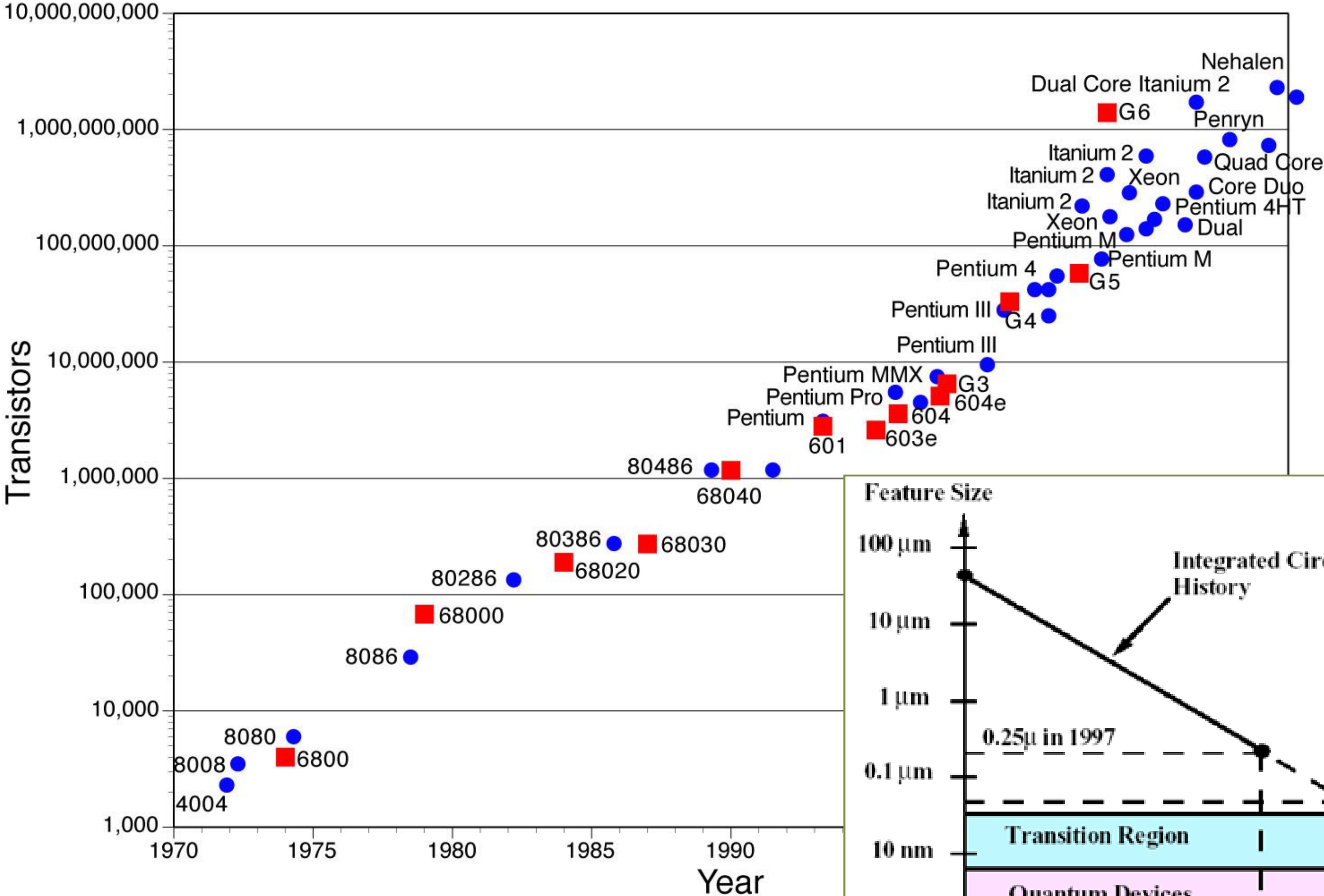
Źródło: Lucas Film

$$|\Psi\rangle \to |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle, |\Psi\rangle \ldots$$



„white page”

NANO era



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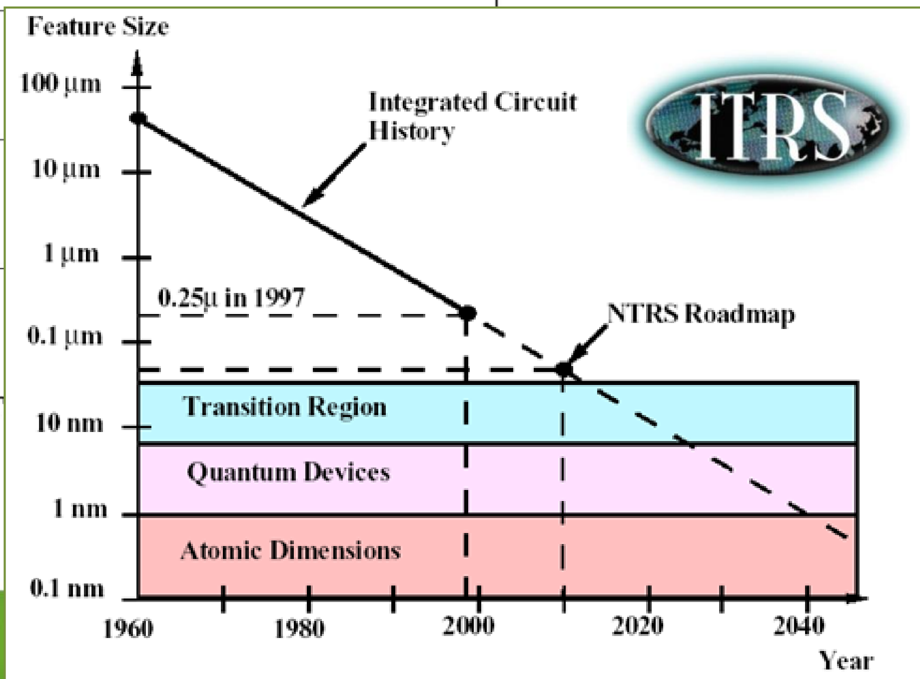
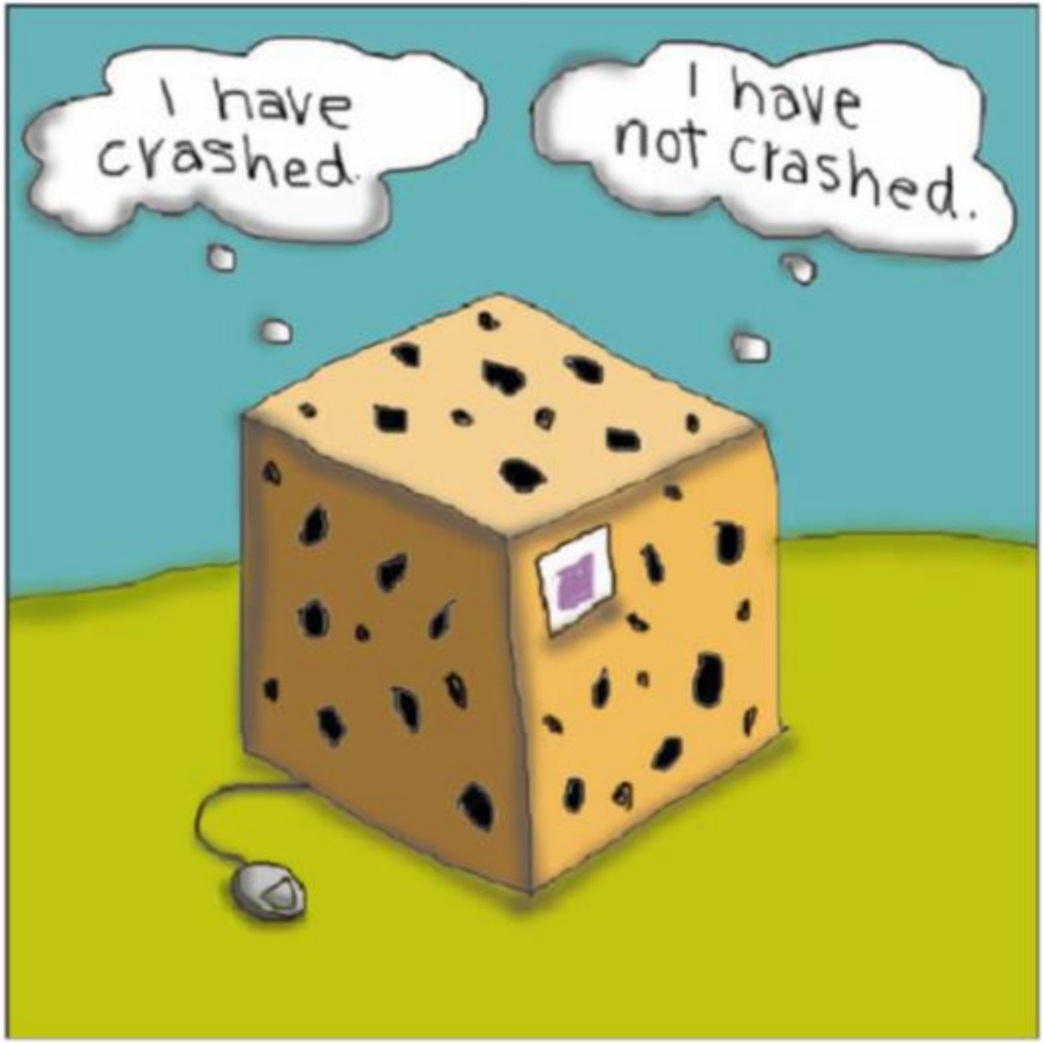
Transistors
1970
1975
1980
1985
1990
Year
4004
8008
8080
6800
8086
68000
80286
68020
80386
68030
80486
68040
Pentium
601
603e
604
Pentium Pro
Pentium MMX
604e
G3
Pentium III
Pentium III
G4
Pentium 4
G5
Pentium M
Pentium M
Xeon
Itanium 2
Itanium 2
Itanium 2
Xeon
Dual
Pentium 4HT
Core Duo
Quad Core
Penryn
G6
Dual Core Itanium 2
Nehalen



Feature Size
100 µm
10 µm
1 µm
0.1 µm
10 nm
1 nm
0.1 nm
Integrated Circuit History
ITRS
0.25µ in 1997
NTRS Roadmap
Transition Region
Quantum Devices
Atomic Dimensions
1960
1980
2000
2020
2040
Year

QWindows



Schrödinger's computer. —Sally O. Lee