Frontiers in Nanoscale Science

Magalí Lingenfelder

MPI-EPFL Laboratory for Molecular Nanoscience

- Introduction to nanoscience
- The art of making nanostructures

Books listed online- reference material

Max Planck Society for the Advancement of Science

- Independent, non-profit organization (an incorporated association), **founded in 1948.**

- Successor to the **Kaiser Wilhelm Society**, which itself was **founded in 1911.**

~1‘810 Mio. € Total budget of the MPS:

80% by the German Federal Government and the individual states,

20% own income & project funding.

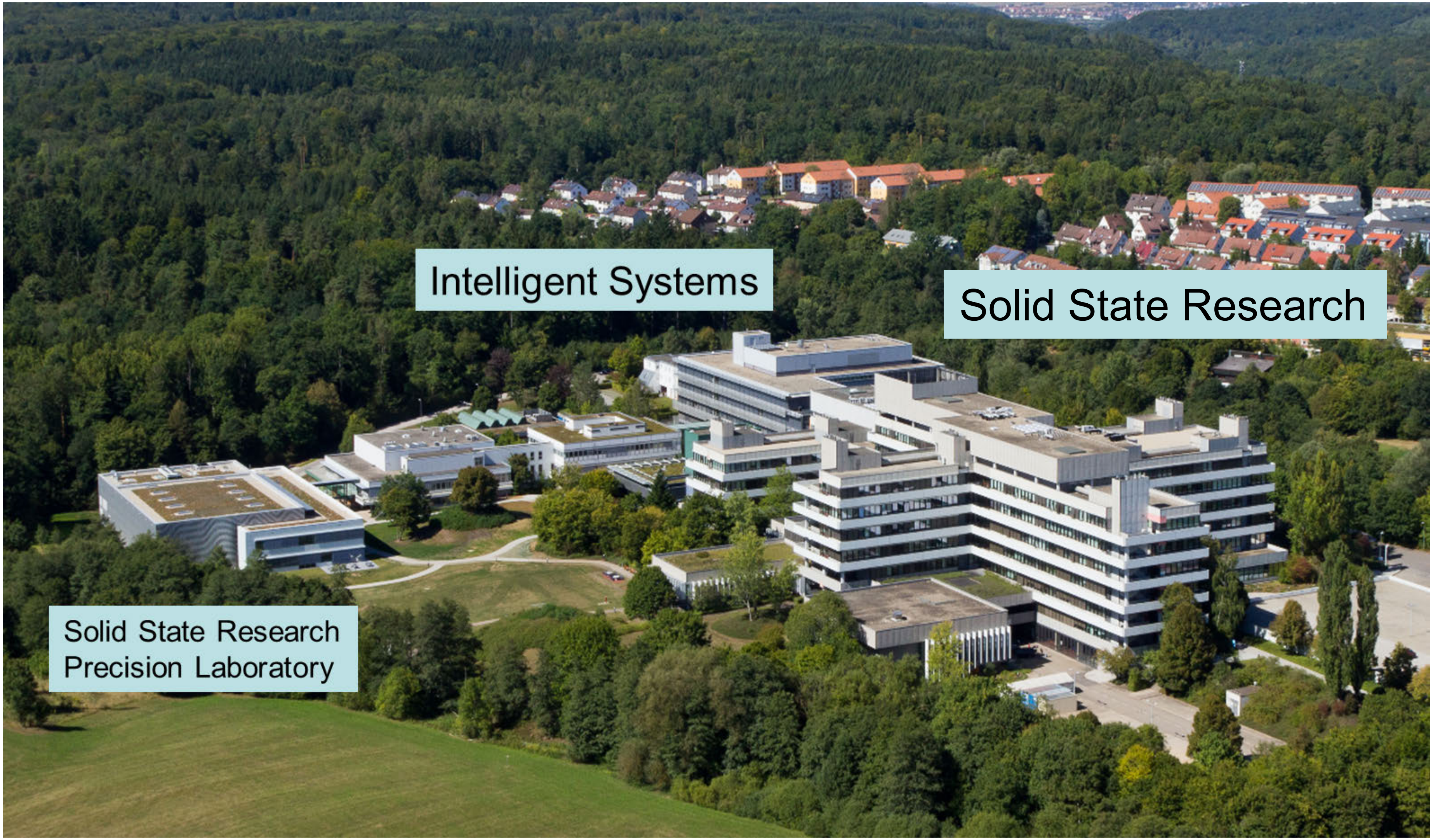
~13‘200 Staff members,

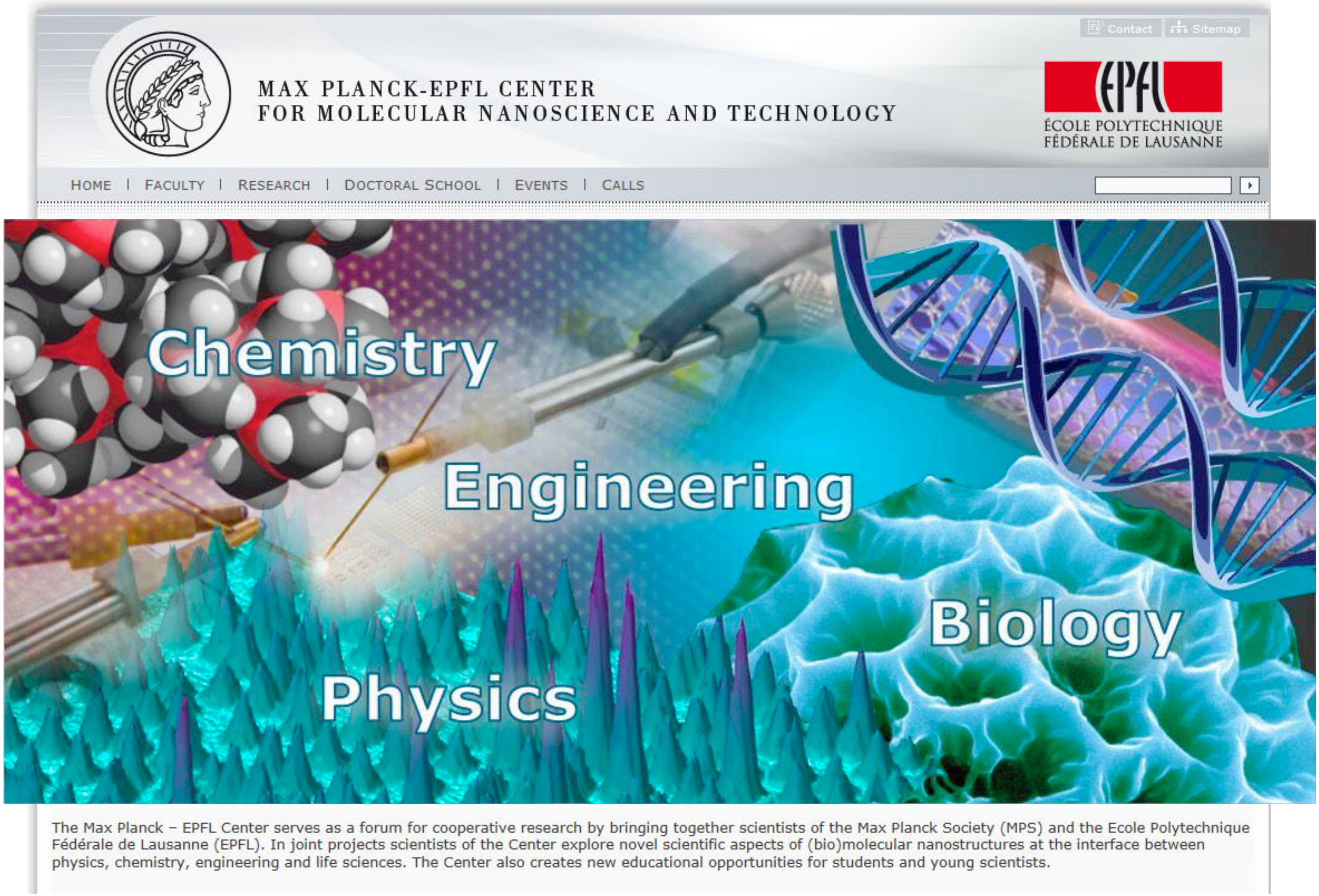
including **~ 5‘200** scientists

~7‘000 Student assistants, graduates, post docs, guest scientists, etc.

83 Max Planck Institutes. 33 Nobel Prizes awarded to their scientists, and is generally regarded as the foremost basic research organization in Europe and the world

Max Planck Campus, Stuttgart





http://mpg-epfl.mpg.de

MPS-EPFL Center MNST

Fritz Haber Institute

Prof. G. Meijer
Prof. M. Scheffler
Dr. V. Blum

MPI Biophys. Chemistry

Prof. H. Grubmüller
Prof. A. Wodtke
Dr. D. Schwarzer

Physics
Prof. H. Brune
Prof. B. Deveaud
Prof. L. Forro
Prof. T. Kippenberg
M. Lingenfelder

Chemistry
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Prof. A. Osterwalder
Prof. T. Rizzo

Materials Science
Prof. A. Fontcuberta
Prof. C. Hébert
Prof. N. Marzari
Prof. F. Stellacci

Life Science
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Prof. S. Maerkl
Prof. A. Radenovic
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Prof. K. Kern
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Prof. B. Lotsch
Dr. K. Balasubramanian
Dr. H. Klauk

MPI Intelligent Systems

Prof. J. Spatz
Dr. P. Fischer
Dr. C. Pacholski
Dr. C. Boehm

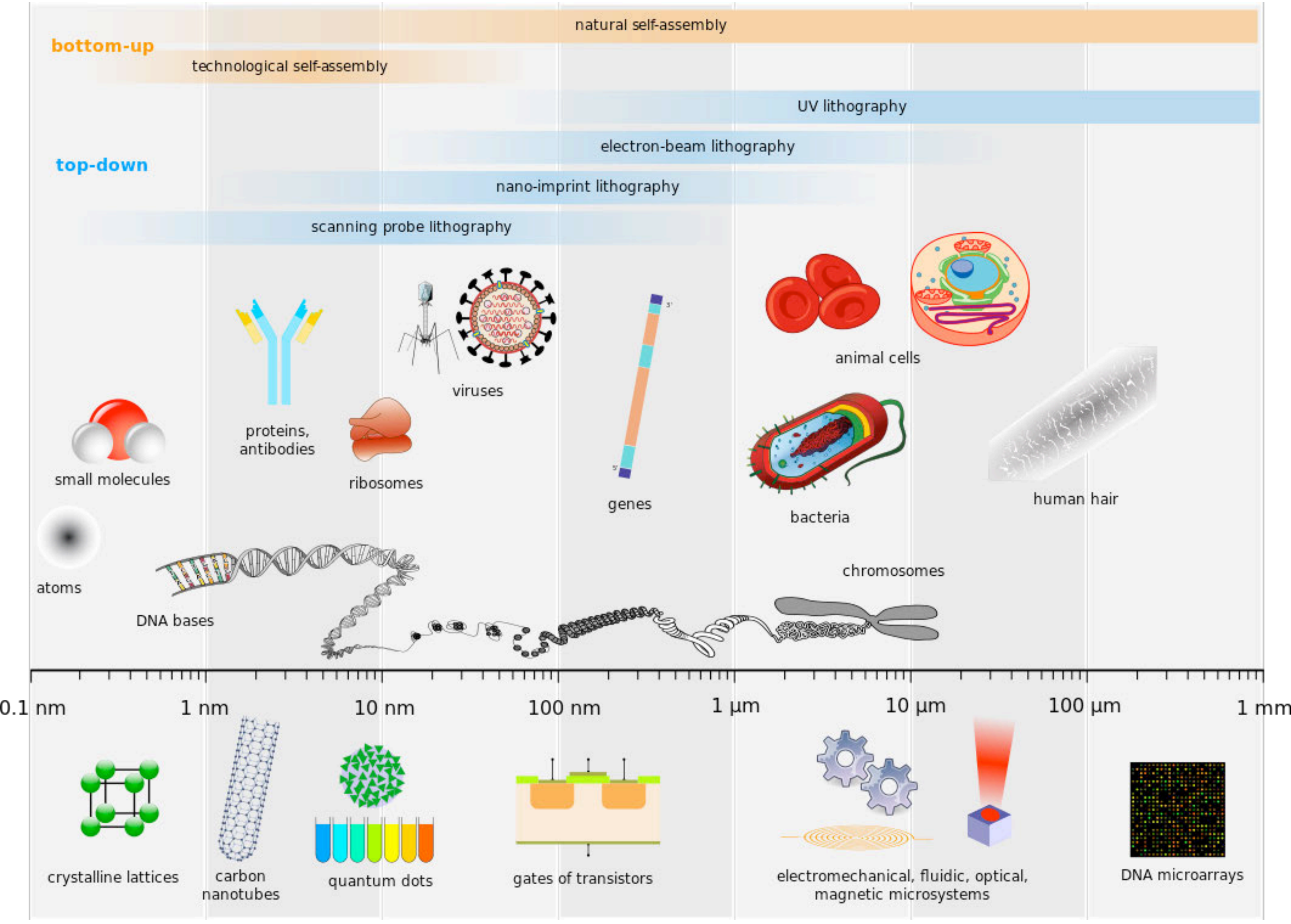
Visiting Max-Planck

December 6/7 2018

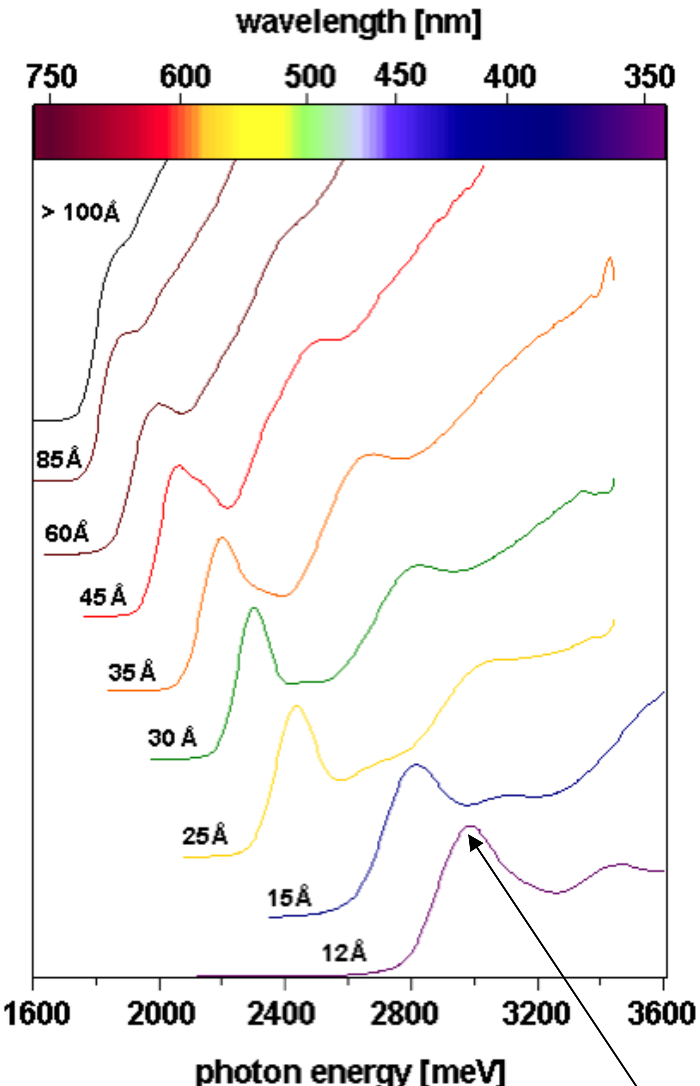
Nanotechnology ?

Nanorobots

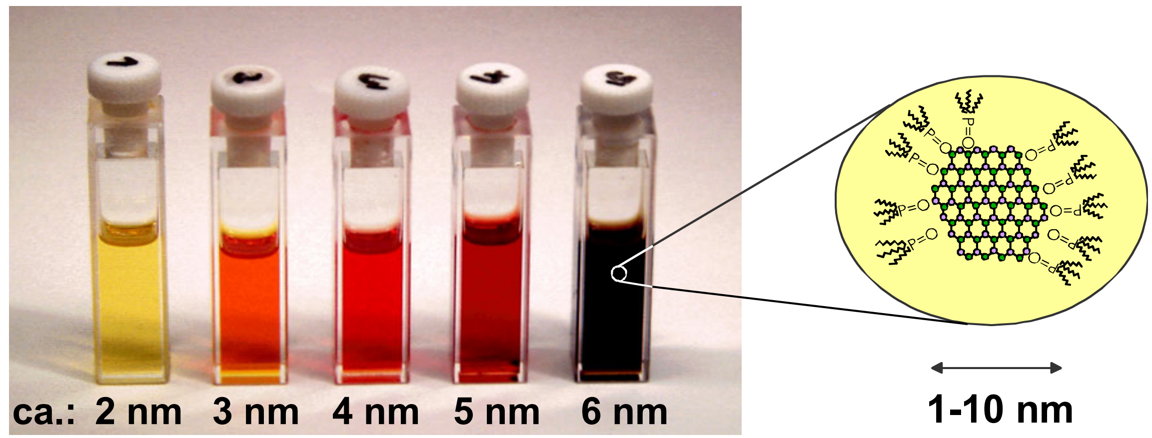
Die Zeit, June 6 (2002)


natural self-assembly
bottom-up
technological self-assembly
UV lithography
electron-beam lithography
top-down
nano-imprint lithography
scanning probe lithography
proteins,
antibodies
viruses
animal cells
small molecules
ribosomes
genes
bacteria
human hair
atoms
DNA bases
chromosomes
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
crystalline lattices
carbon
nanotubes
quantum dots
gates of transistors
electromechanical, fluidic, optical,
magnetic microsystems
DNA microarrays

Size-dependence of optical absorption



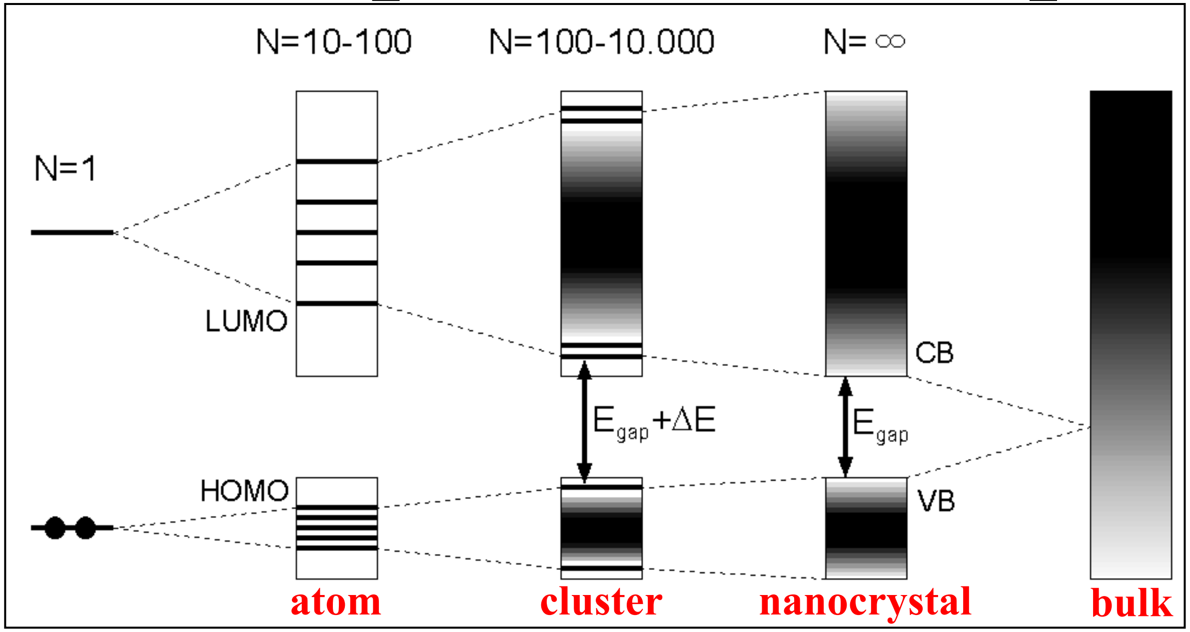
CdSe nanocrystals



- very large molar extinction coefficients (how strongly a substance absorbs light at a given wavelength) (1-5 x 10^6 M^{-1} cm^{-1}), ~ 10-50 times larger than that of organic dyes

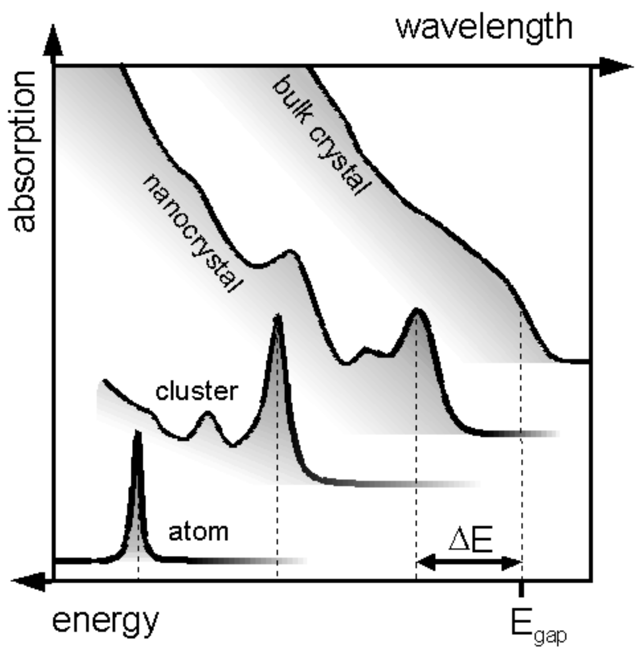
excitonic peak (e-hole pair)

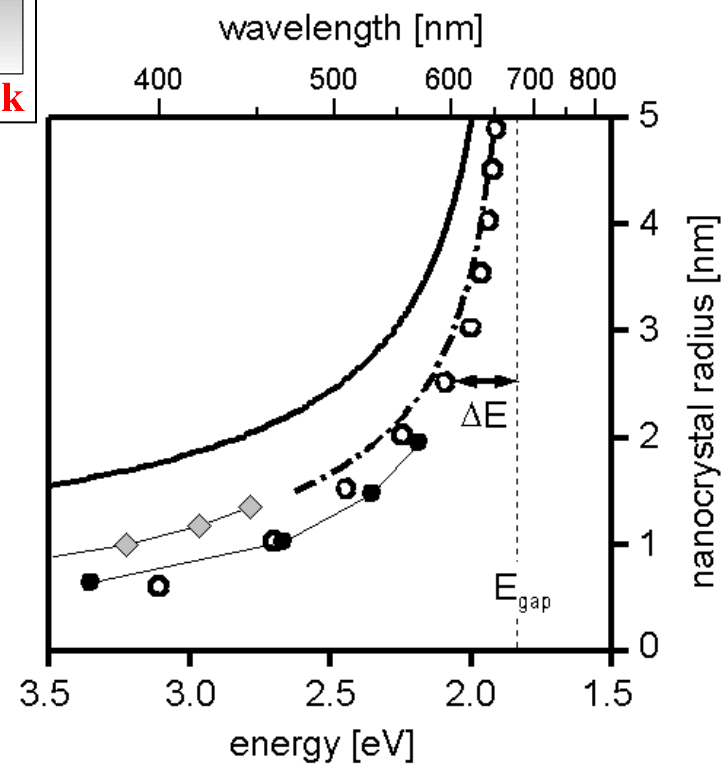
Size-dependence of optical absorption



QUANTUM CONFINEMENT

band gap as a function of nanocrystal size:

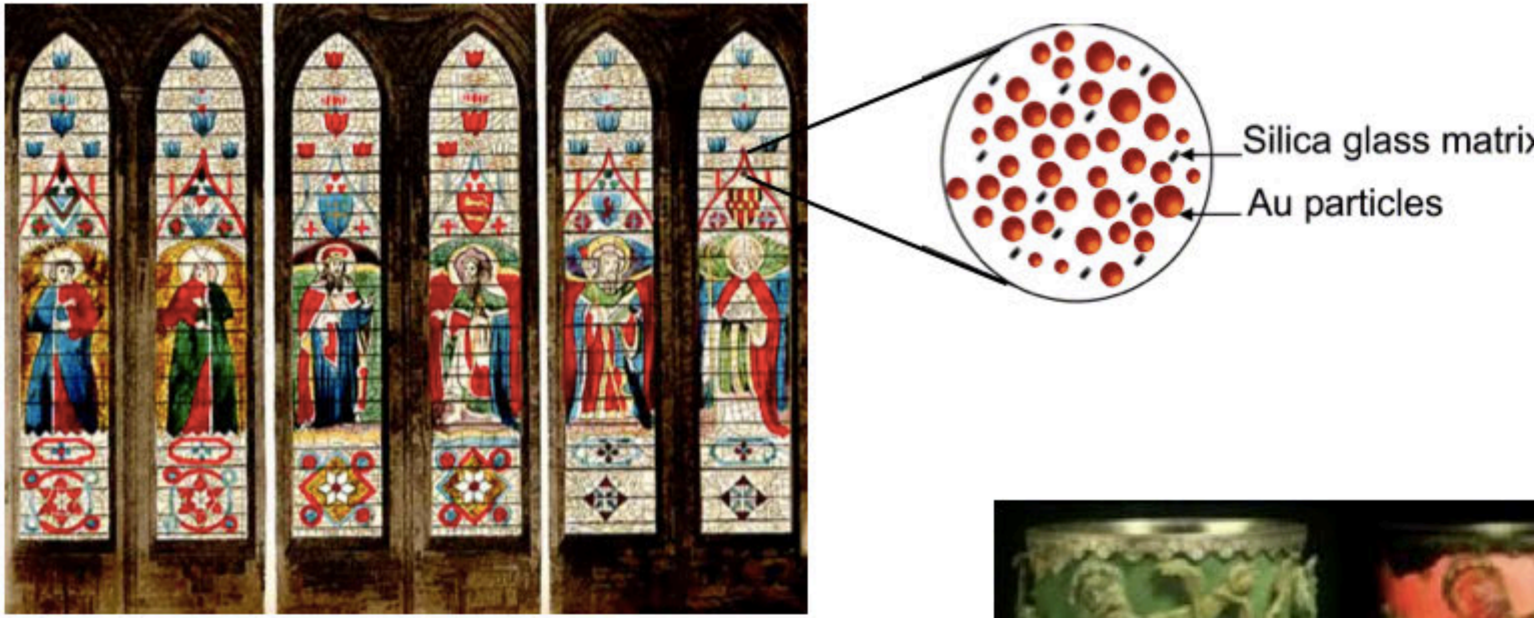




Inorganic:

CB min

VB max



Westminster Abbey,
East-Window

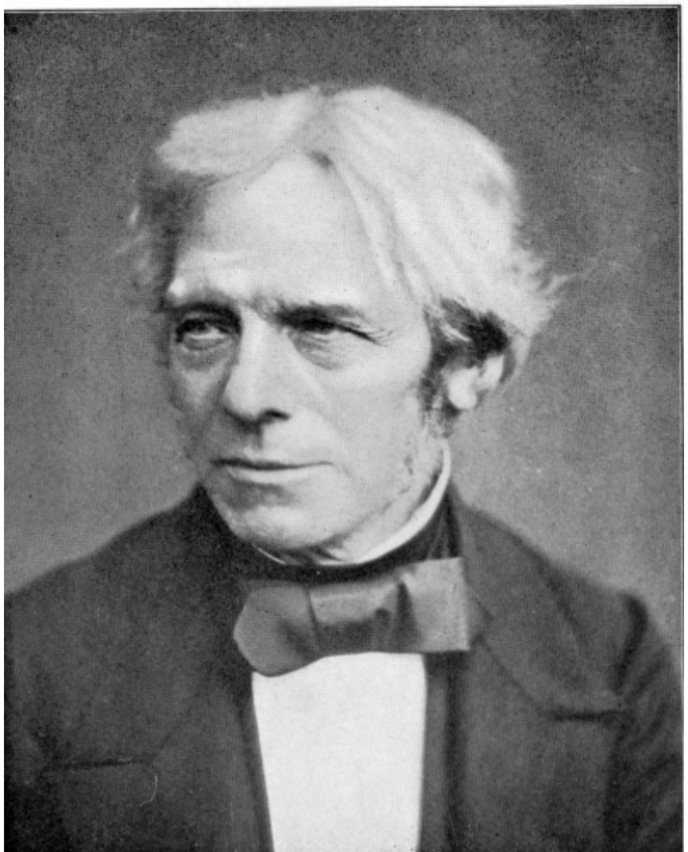
Medieval Nanotechnology

Lycurgus Cup

FARADAY'S *Gold*

a catalog of his 1856 specimens

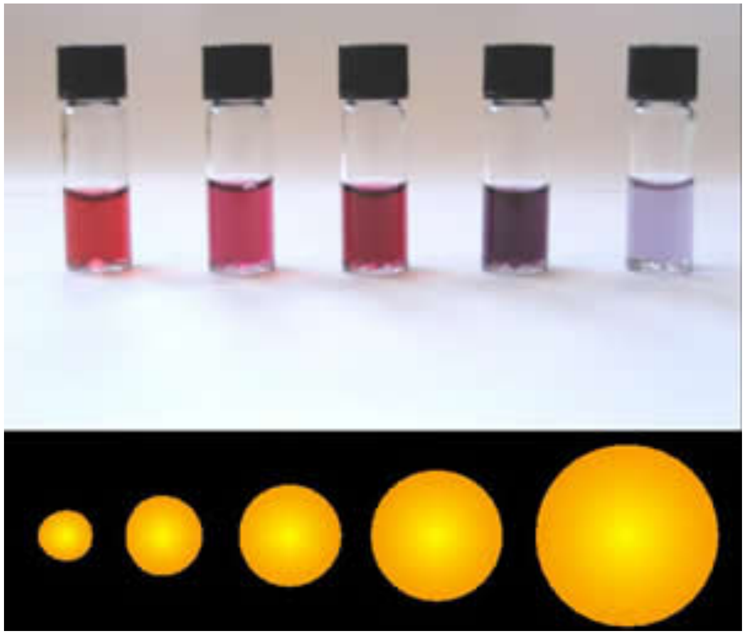
by
RYAN D. TWENEY
with the assistance of
NEIL BERG
and
JEFF FRIEDRICH



Michael Faraday discovered in **1851** that the colors of ruby gold were due to its finely divided state.

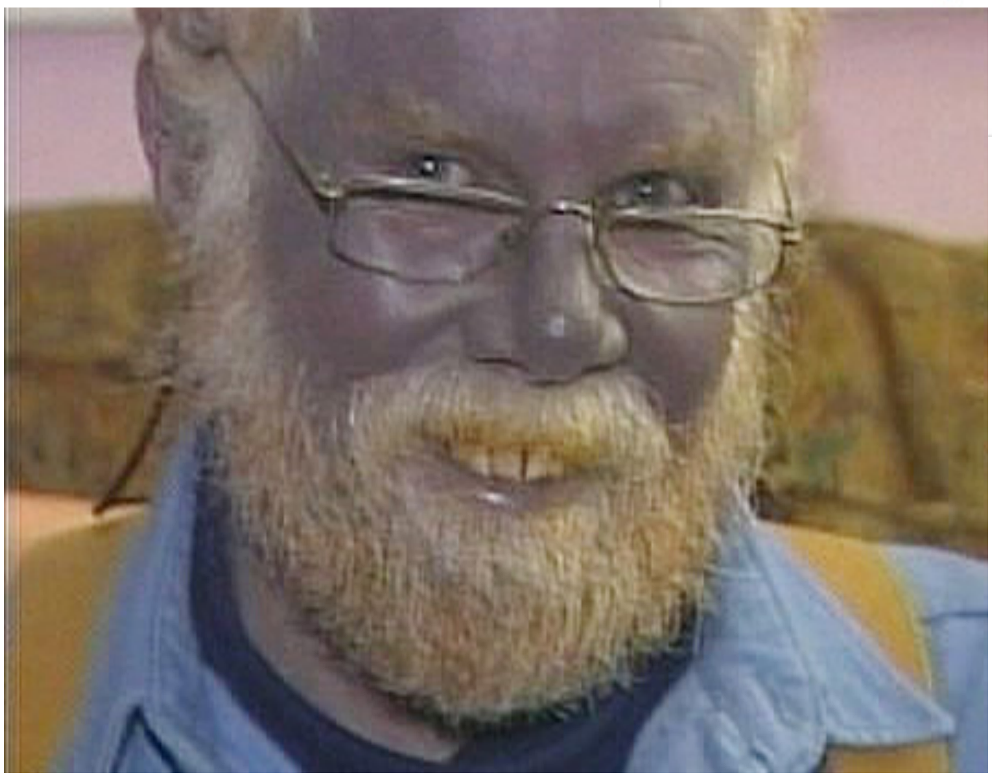
Original Au colloids still on display at the Royal Institution.

Everlasting Beauty

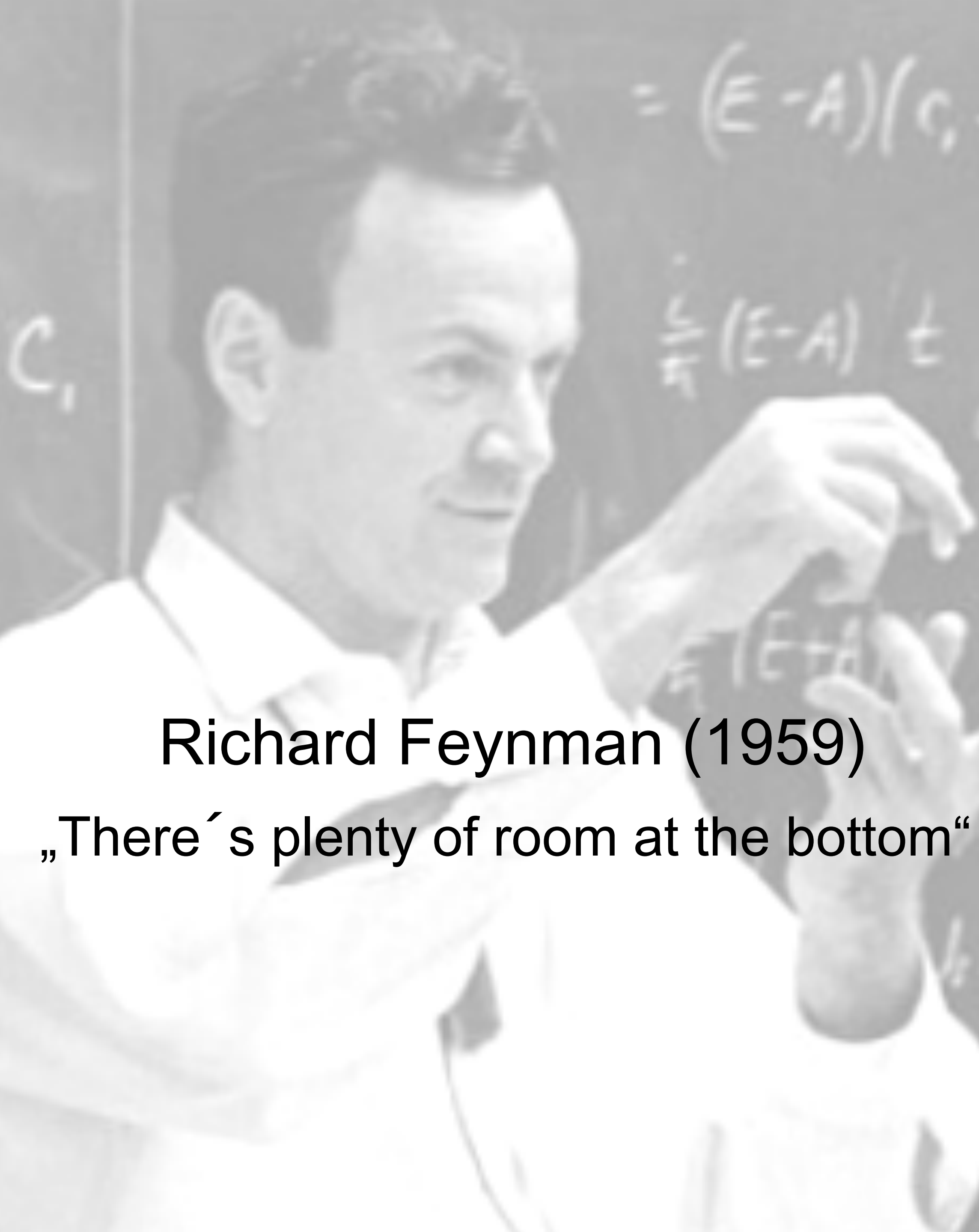


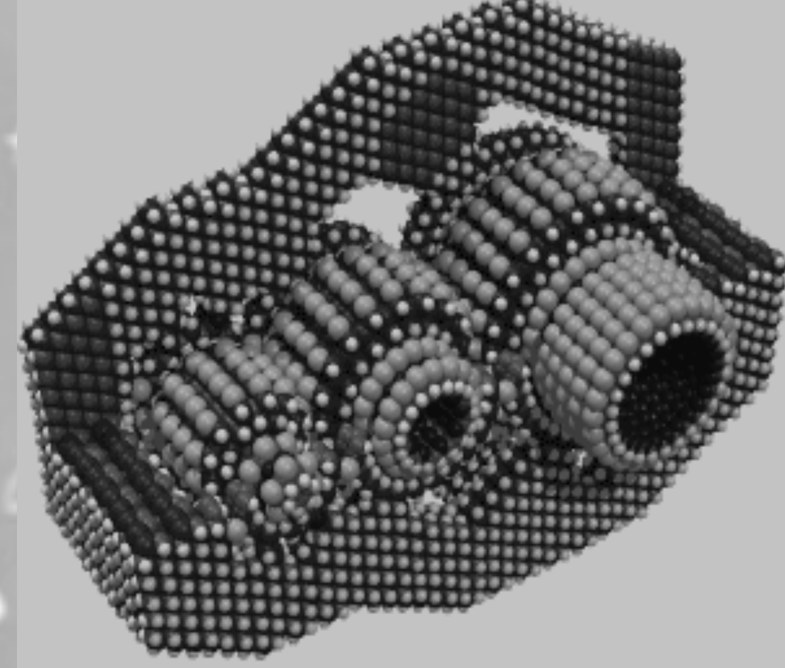
According to experts, the colloidal gold is absorbed through the skin and helps stimulate incorporation blood circulation, increasing enzyme activity, restoring and reconstructing the damaged cells. Also induces the addition of mineral nutrients, while preventing skin sagging. In addition, gold nanoparticles eliminate biological contaminants generated by the body and encapsulated in clogged pores. This is one of several causes of tired, prematurely aged and dull skin.

„Blue Man“ Paul Karason



$Ag^+ + h\nu \rightarrow Ag$ (BLUE)



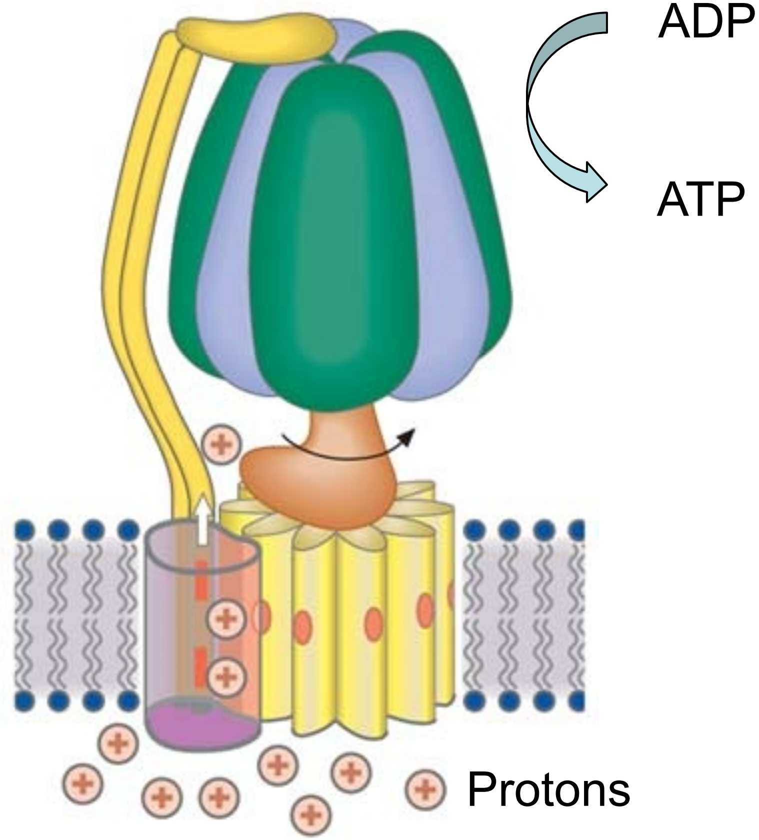


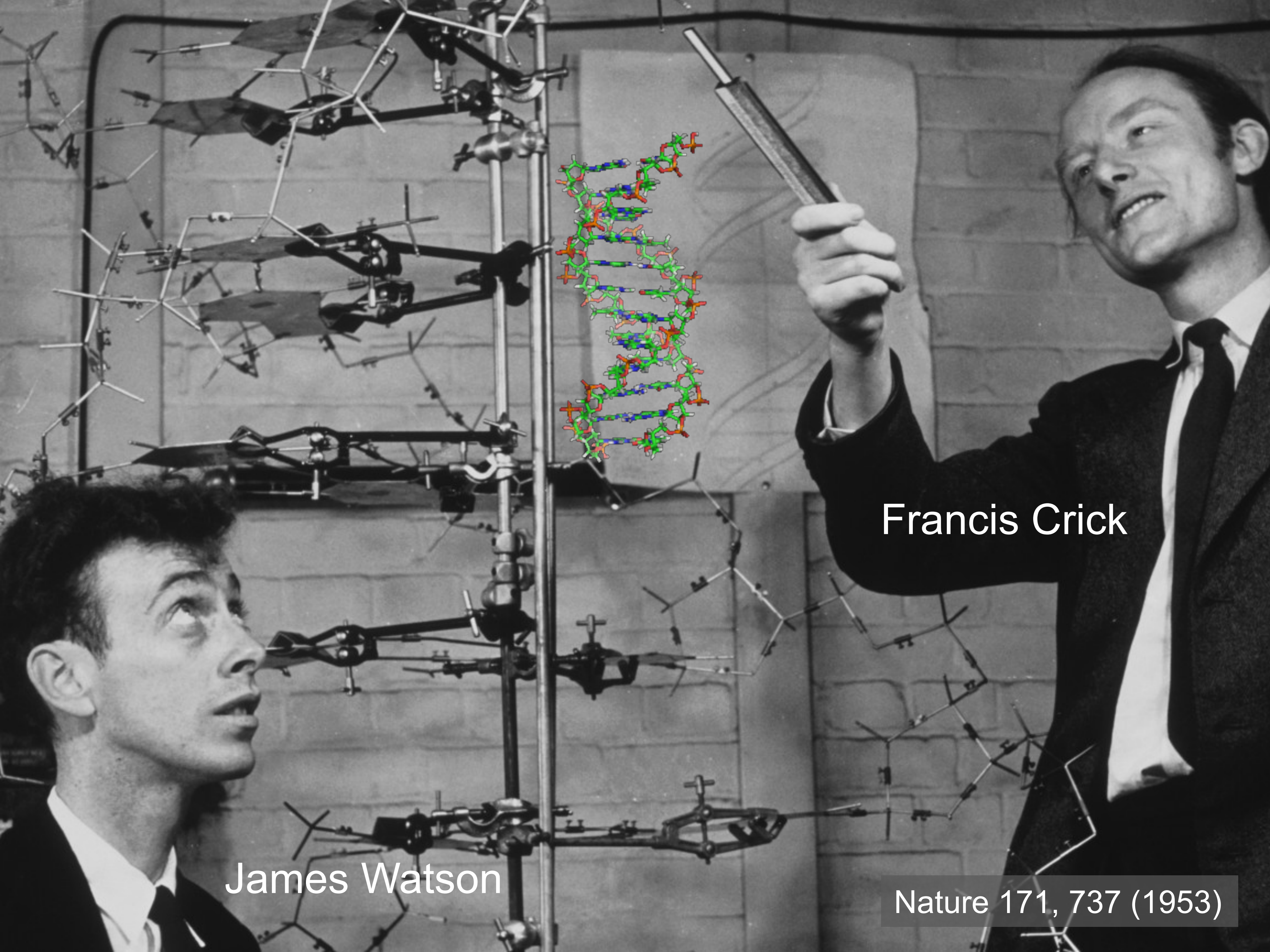
Richard Feynman (1959)

„There´s plenty of room at the bottom“

Molecular Machines

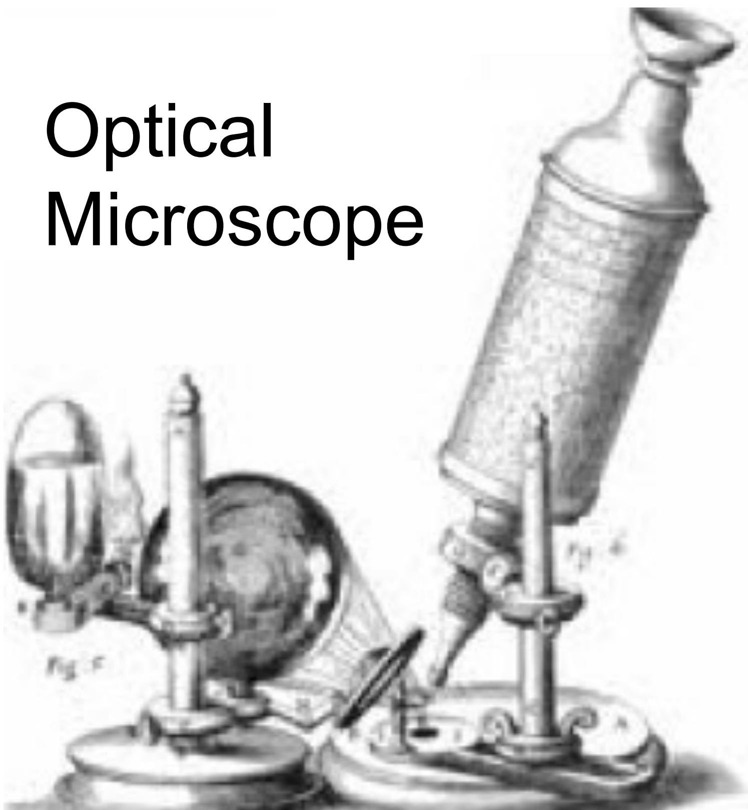
ATP Synthase

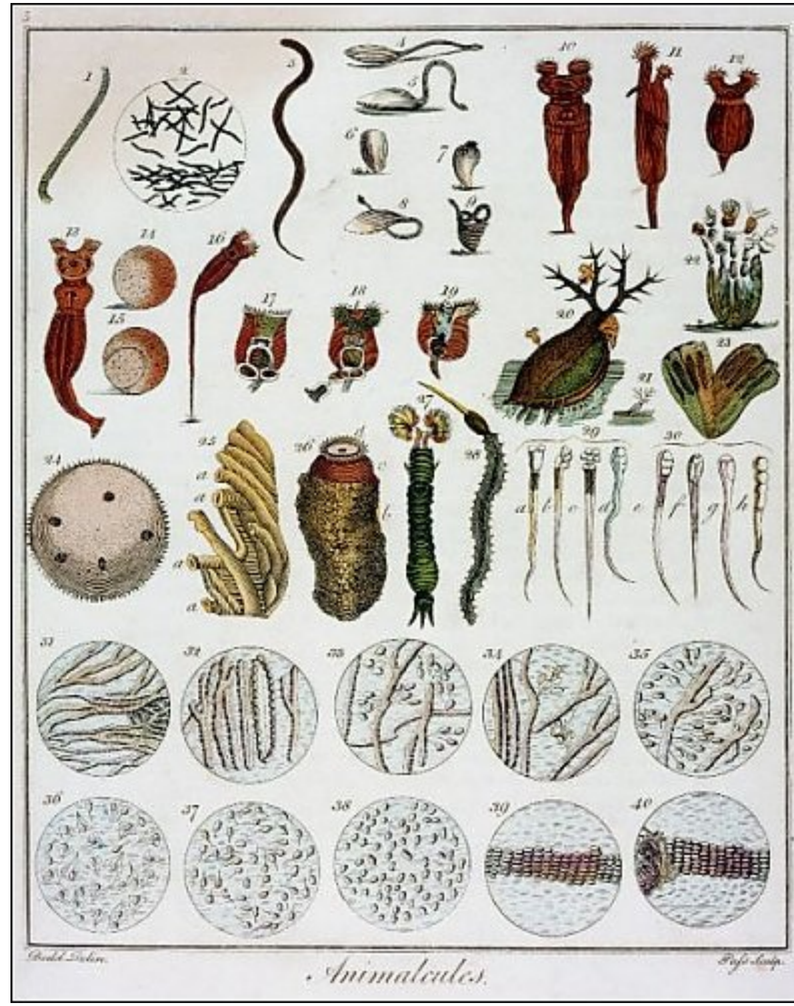



Francis Crick
James Watson
Nature 171, 737 (1953)

„Enlightenment“

Optical
Microscope





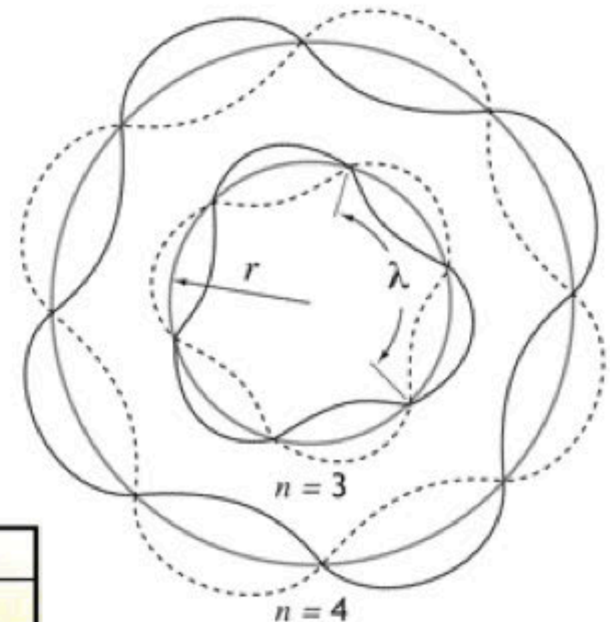
Robert Hooke (1635-1703)
Antoni van Leeuwenhoek (1632-1723)

Quantum Mechanics: Matter as Waves

De Broglie Wavelength

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

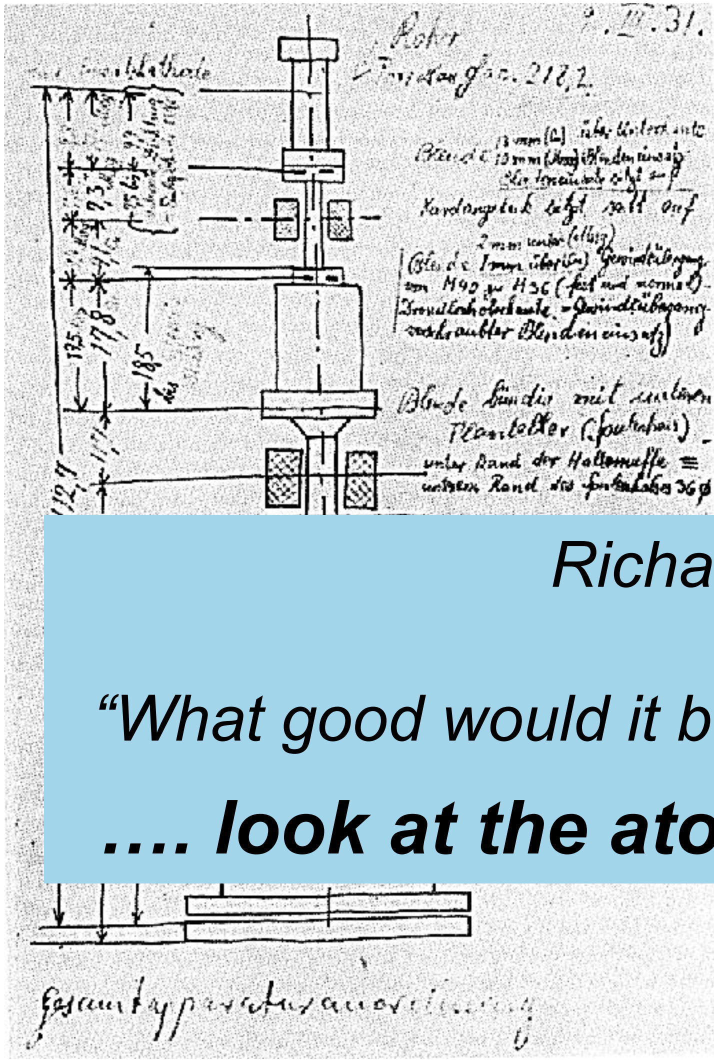
λ = wavelength
h = Planck's constant (6.63×10^{-34} J • s)
p = momentum
m = mass
v = speed

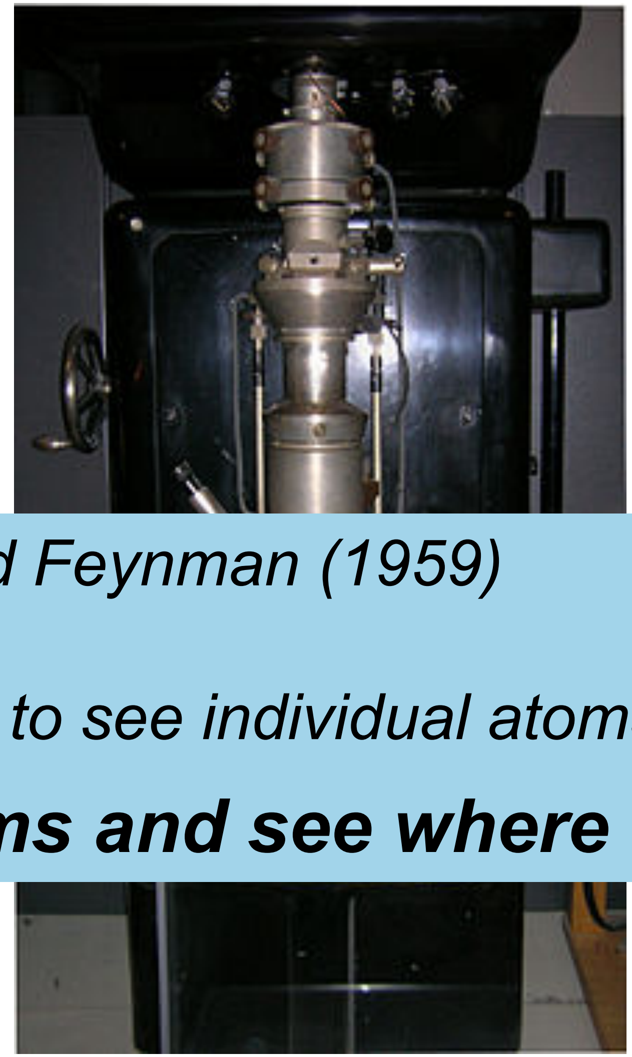


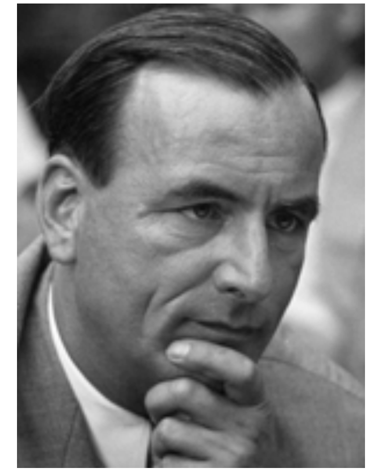
Particle:	Particle energy E_0 (eV)						
	1	10	10^2	10^3	10^4	10^5	10^6
photons	1240 0	1240	124	12.4	1.24	0.124	0.012
electrons	**12.3**	**3.89**	**1.23**	**0.39**	**0.12**	**0.037**	**8.7e-3**
protons	0.29	0.091	2.9e-2	9.1e-3	2.9e-3	9.1e-4	2.8e-4

particle wavelength (Å) at various energies

Electron-Microscope





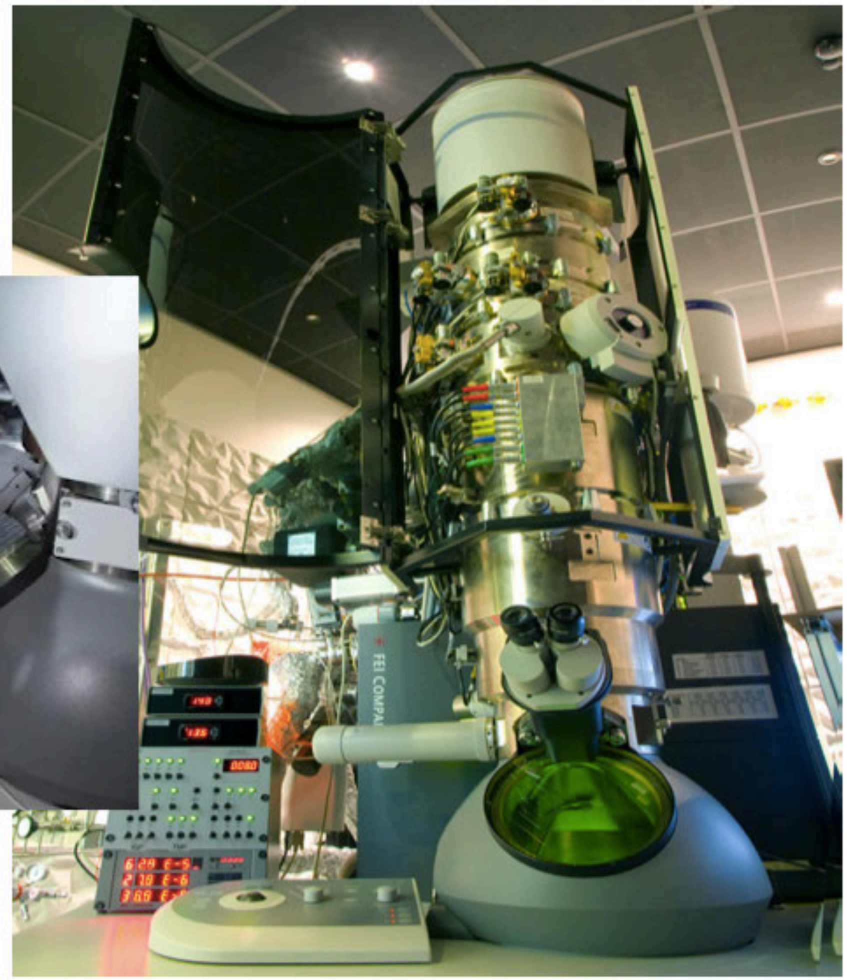


Richard Feynman (1959)

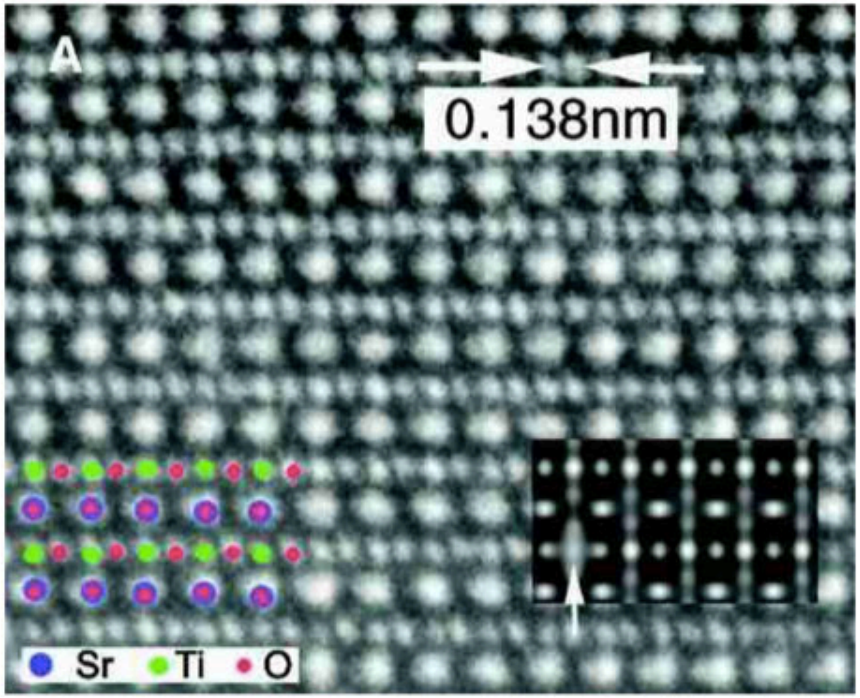
"What good would it be to see individual atoms distinctly?

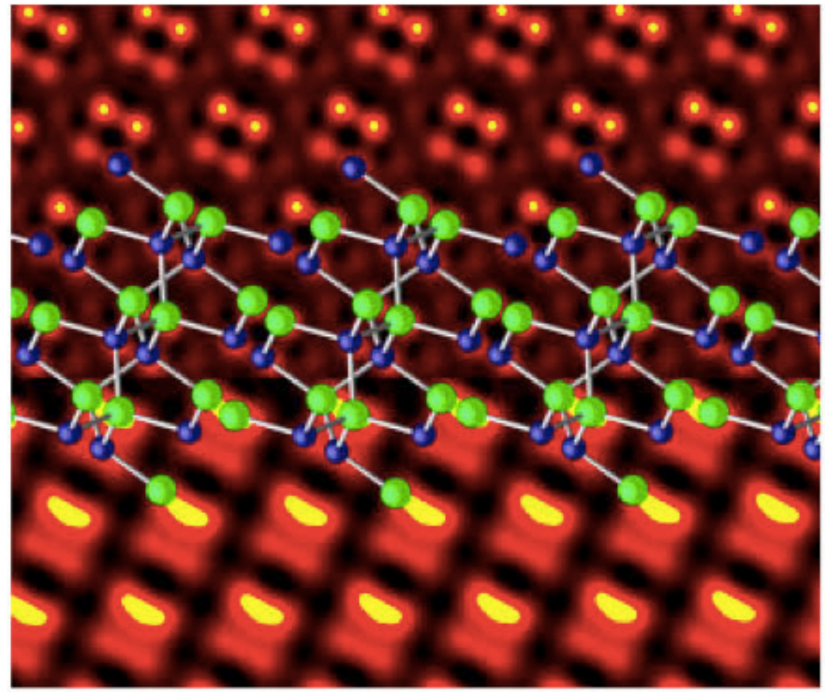
***…. look at the atoms and see where they are**."*

Titan Transmission-Electron-Microscope



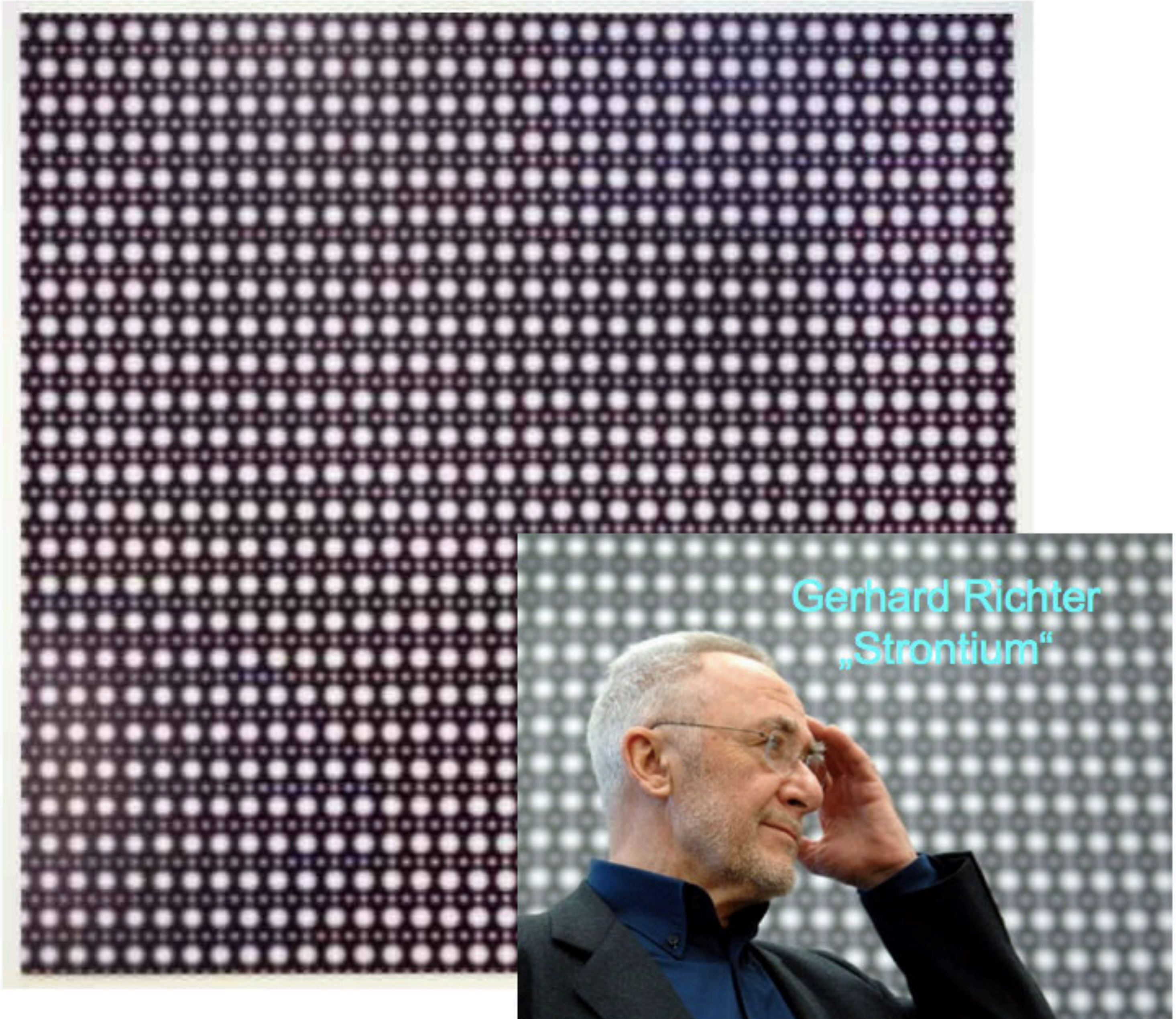
Atomic Resolution



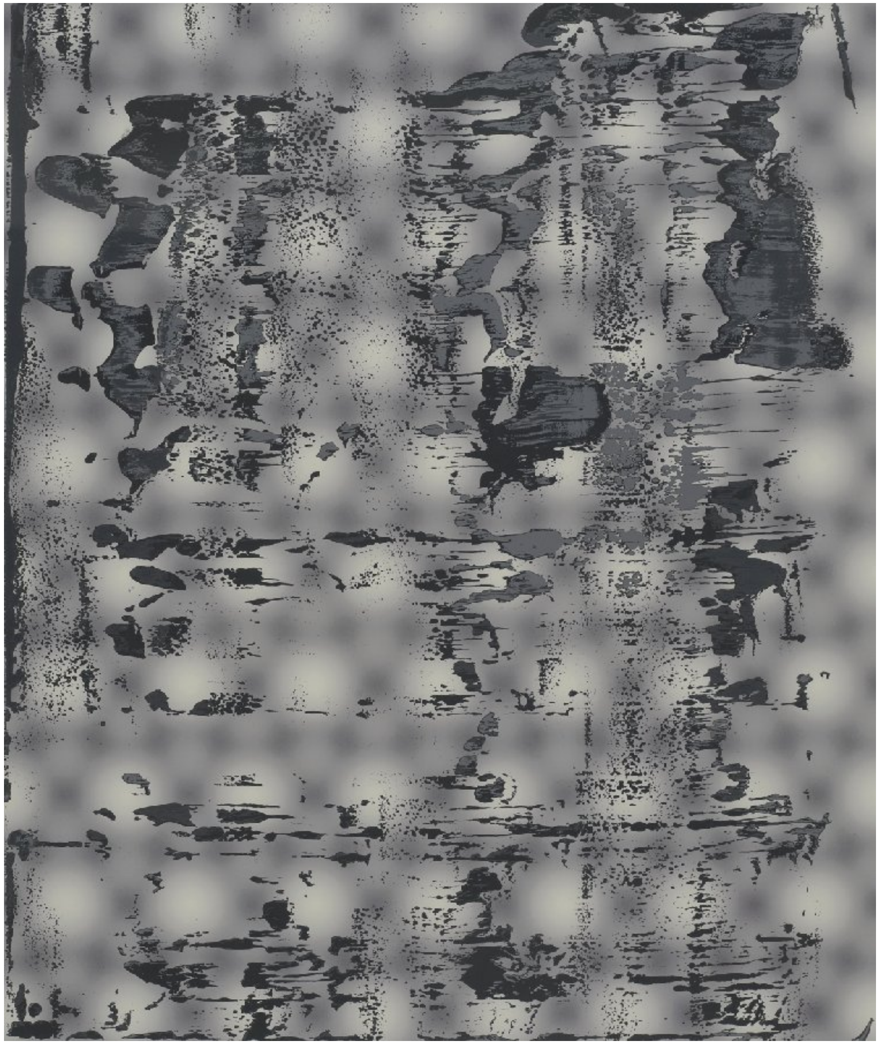


Strontiumtitanate

Aluminiumnitrid

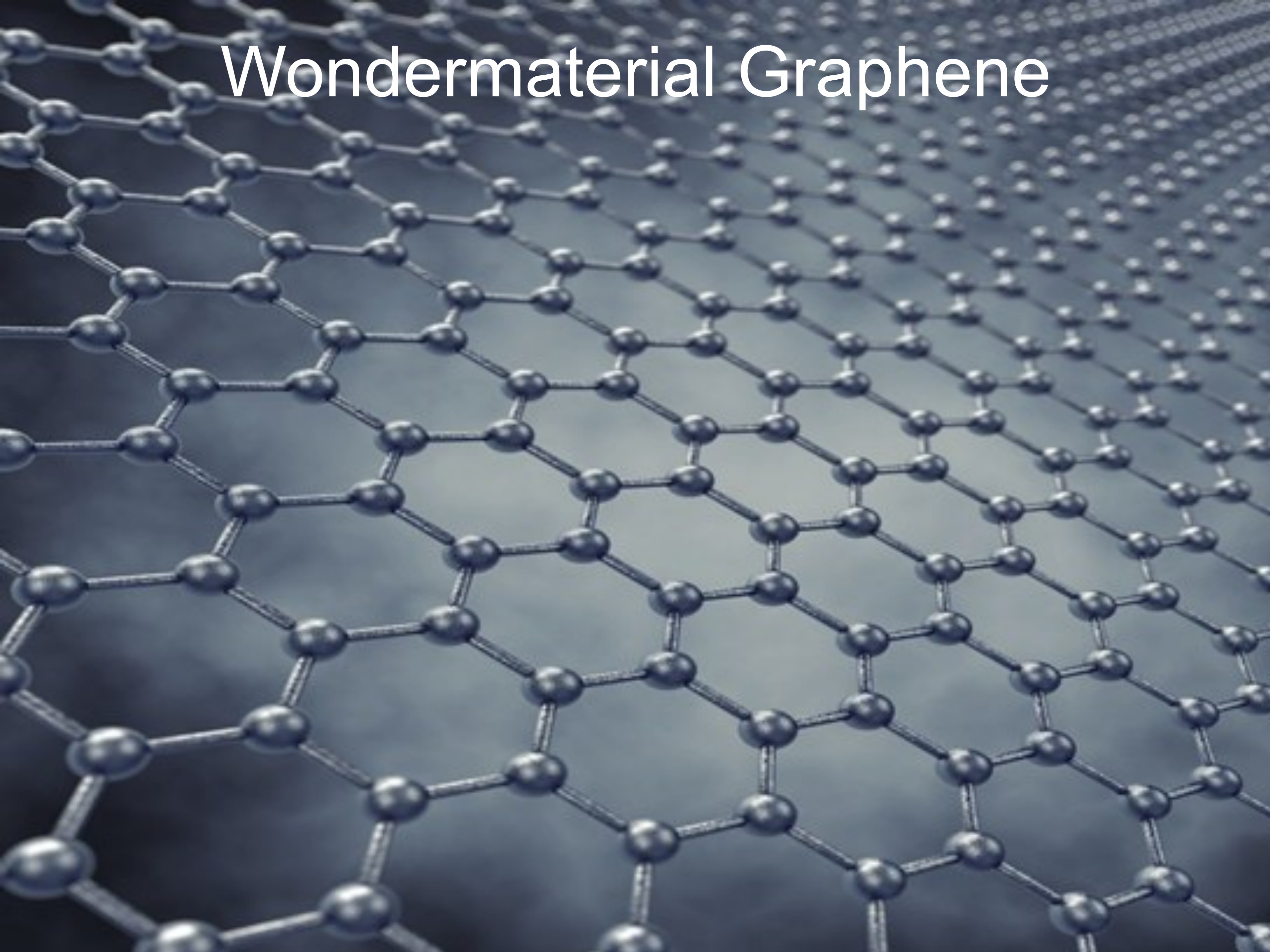


2005, De Young Museum San Francisco



Gerhard Richter, "Graphit", 2005

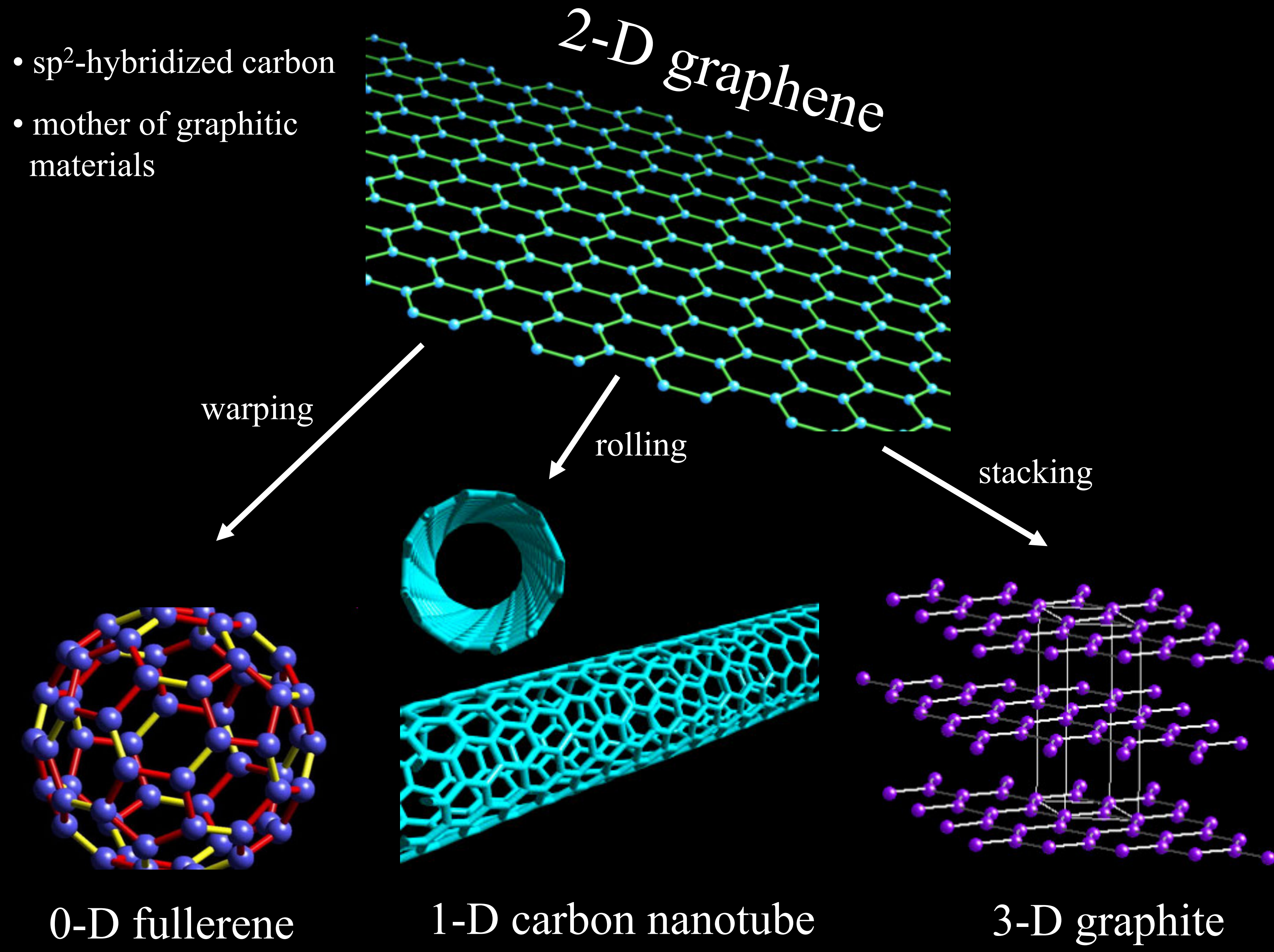
Wondermaterial Graphene



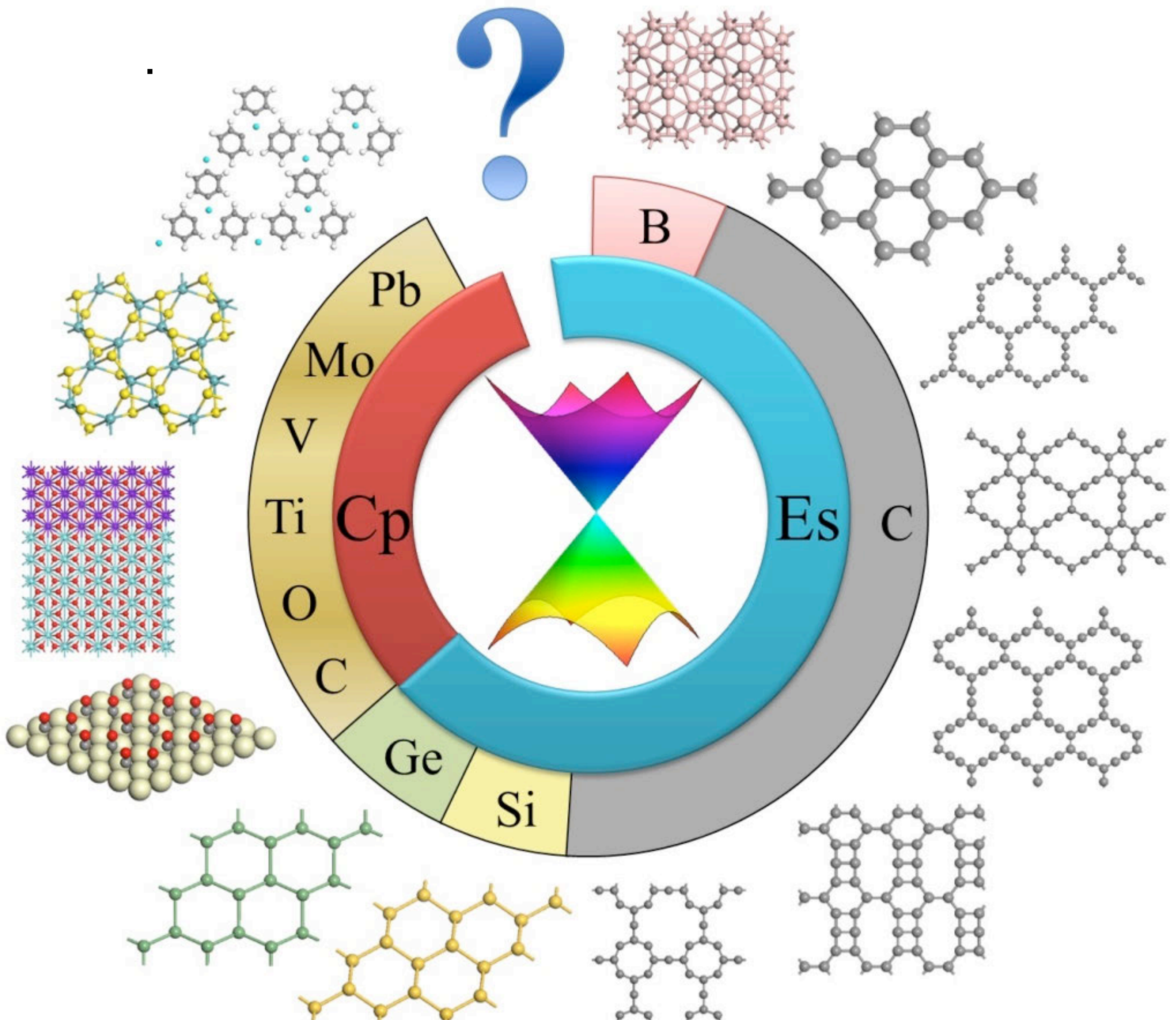
Wondermaterial Graphene

thinnest imaginable material (few Å)
largest surface area (~2700 m^2/g)
strongest material (theoretical limit)
stiffest known material (stiffer than diamond)
most stretchable crystal (up to 20% elastically)
record thermal conductivity (outperforming diamond)
highest current density at RT (10^6 times of copper)
completely impermeable (even He atoms cannot squeeze through)
highest intrinsic carrier mobility (100x larger than Si)
lightest charge carriers (zero rest mass)
largest mean free path (micron range)

https://www.youtube.com/watch?v=EIRc4Eu2PUQ

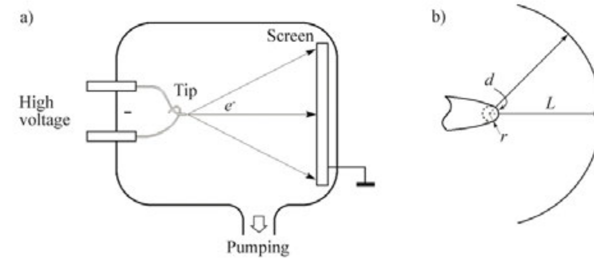

• sp^2-hybridized carbon
• mother of graphitic materials
2-D graphene
warping
rolling
stacking
0-D fullerene
1-D carbon nanotube
3-D graphite

2D Dirac Materials



Crystalline materials consisting of a single layer of atoms. Conic electronic band structures. Unusual transport properties. Massless fermions Ultra high carrier mobility

Images of Atoms

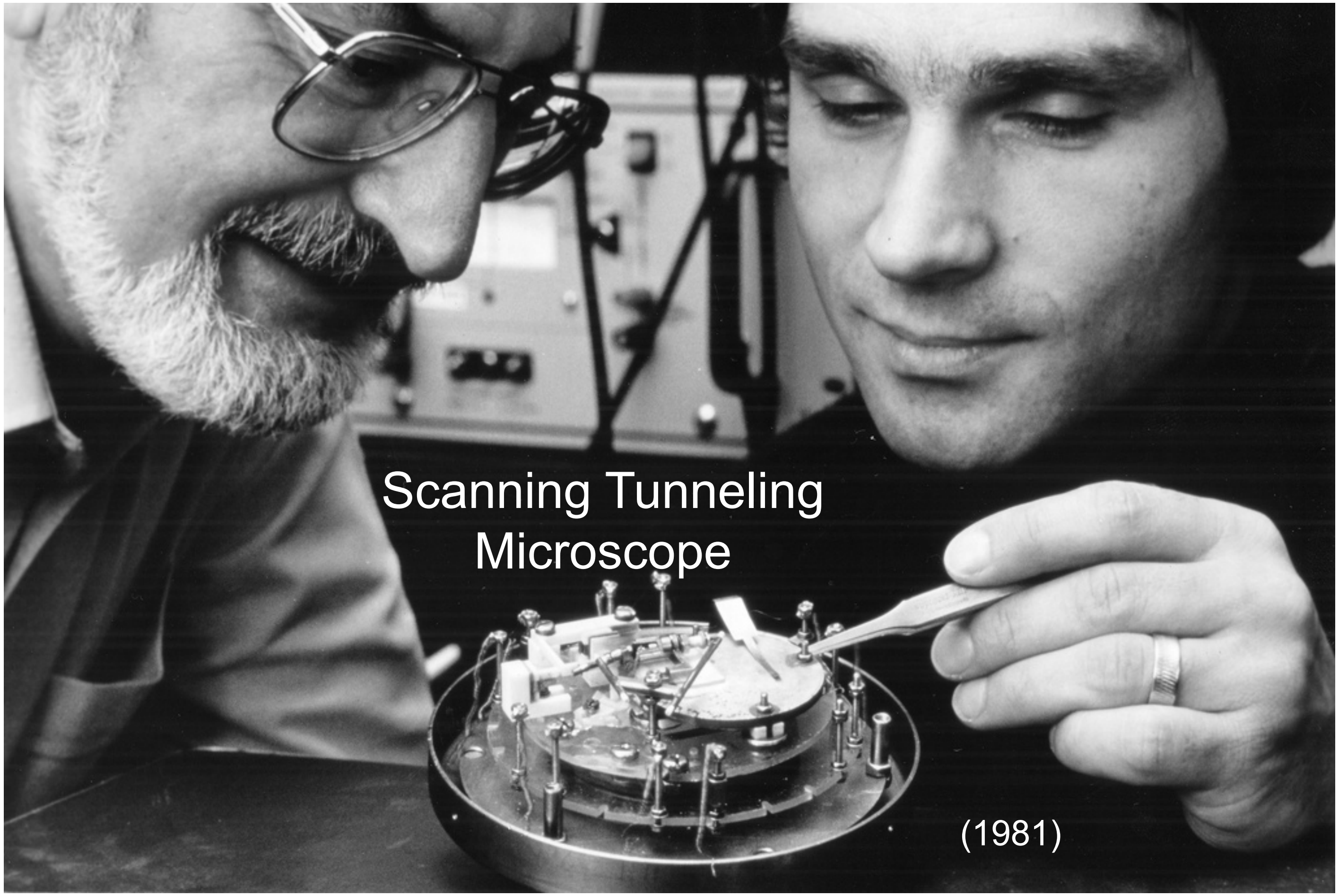


Erwin Müller ➔ Field Ion Microscopy (1951)

The sample is held at a large negative potential (1-10 kV) relative to the fluorescent screen.

first atomic images (1955)

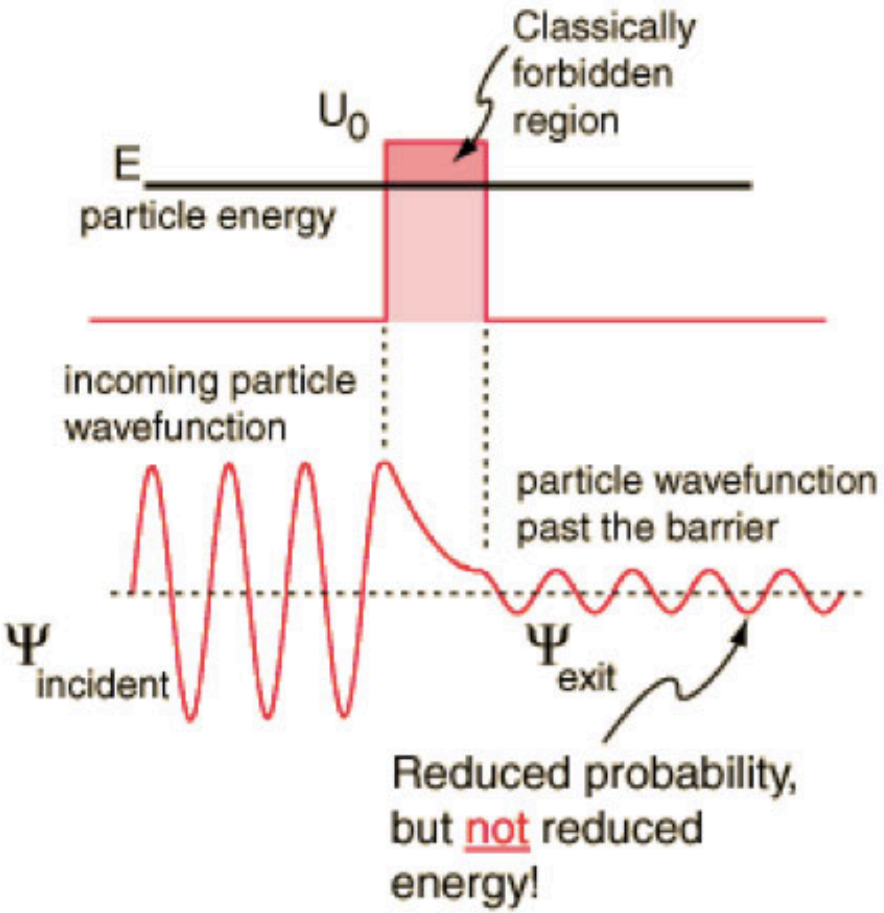
„Sensing“ Atoms

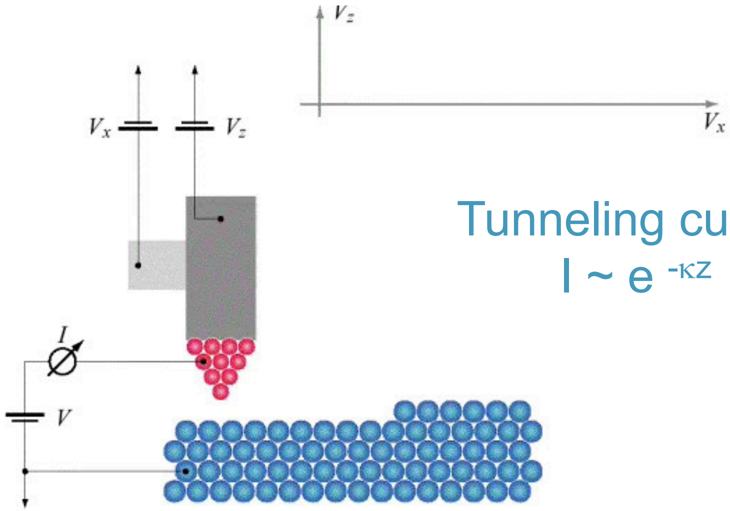


Heini Rohrer

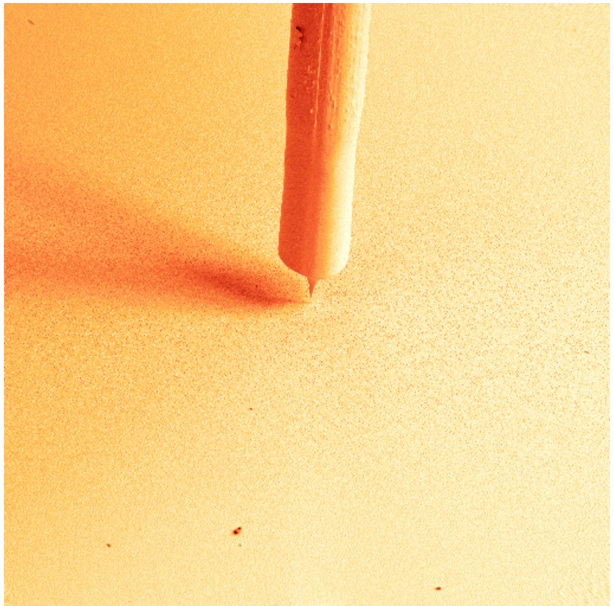
Gerd Binnig

Quantum Mechanics: Tunneling





Tunneling current
$I \sim e^{-\kappa z}$

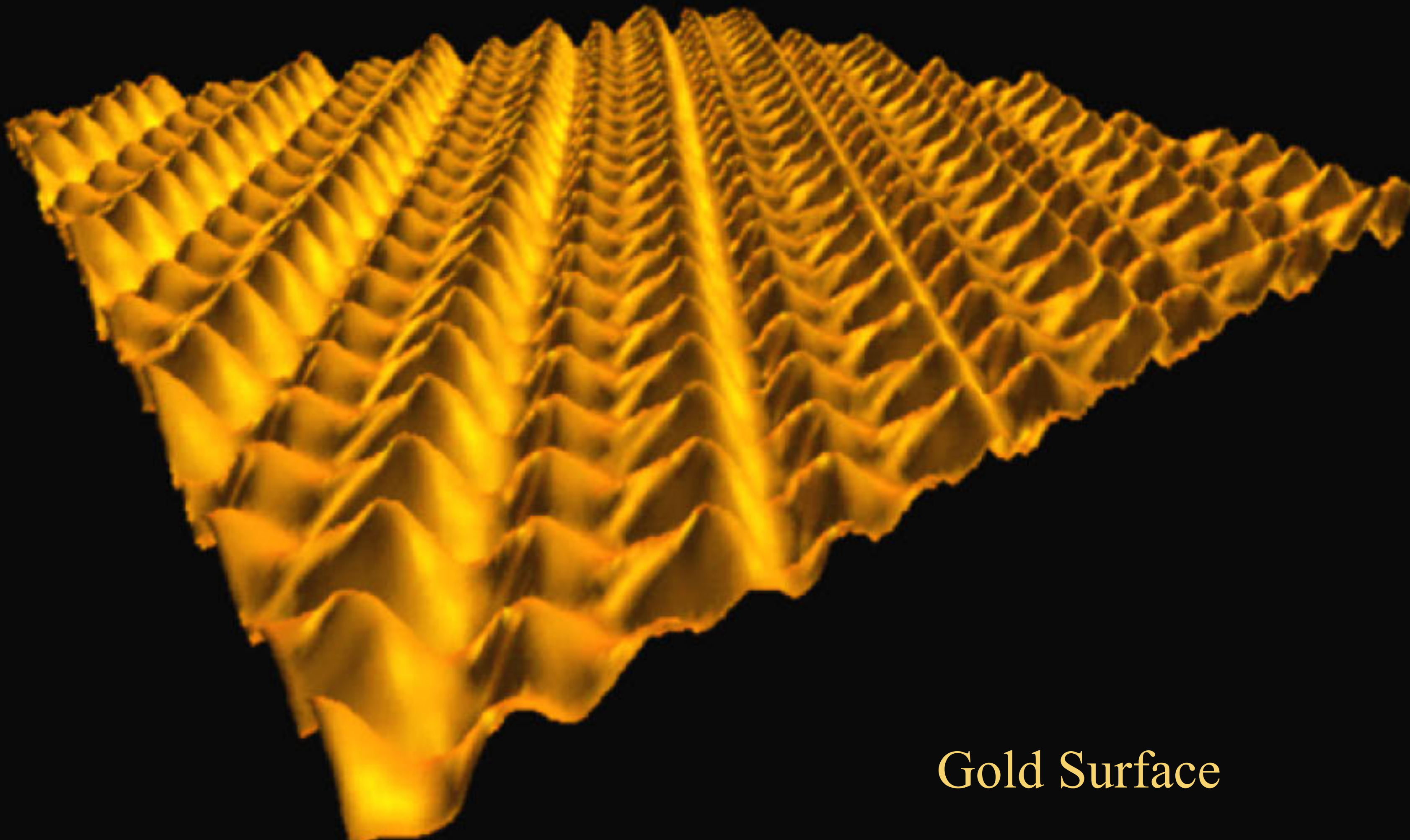


using an exsiccator as vacuum chamber and

lots of Scotch tape….

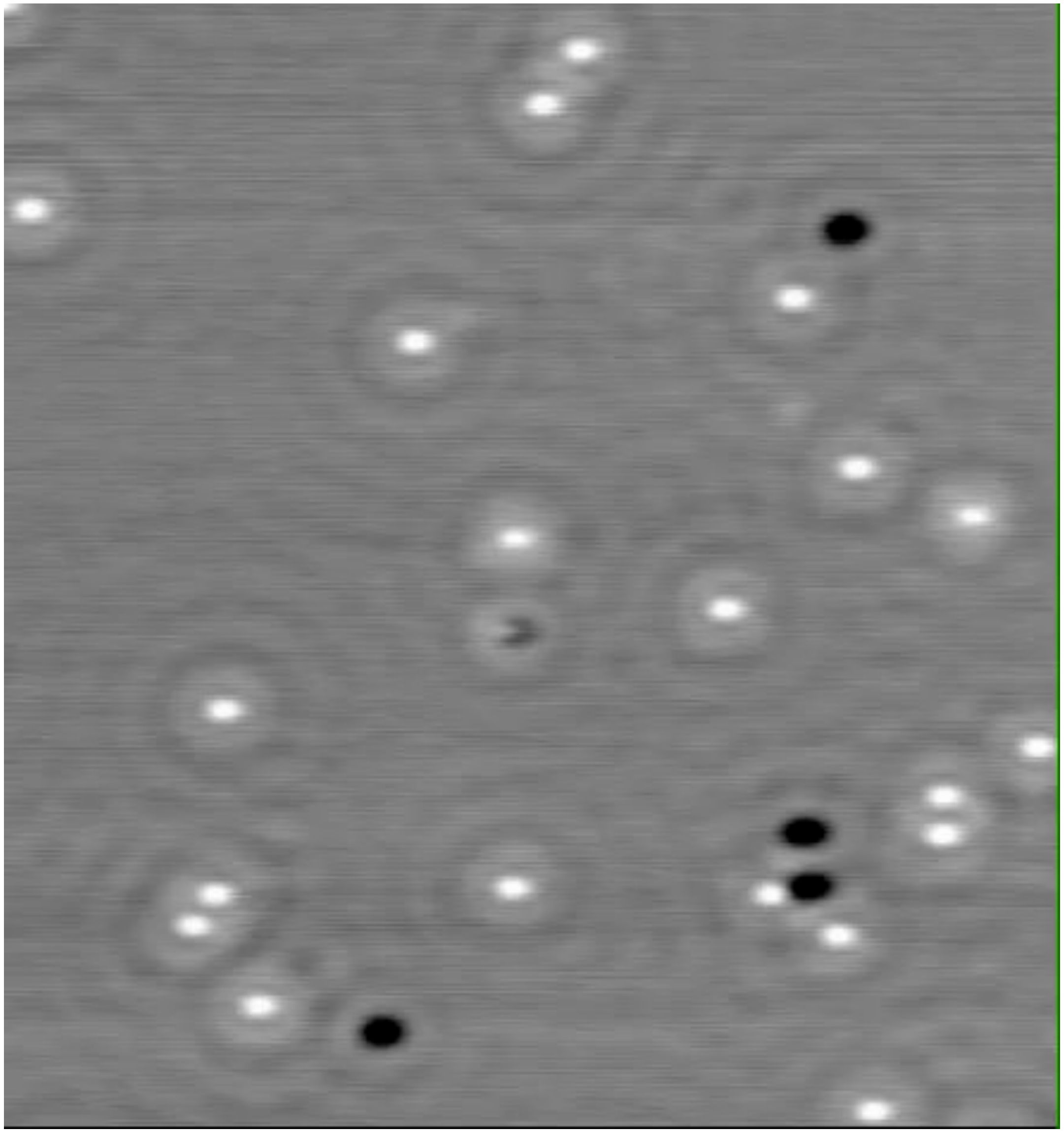
"I could not stop looking at the images. It was like entering a new world"

G. Binning, joint Nobel lecture with H. Rohrer, December 8, 1986.



Gold Surface

Cu Atoms at Work

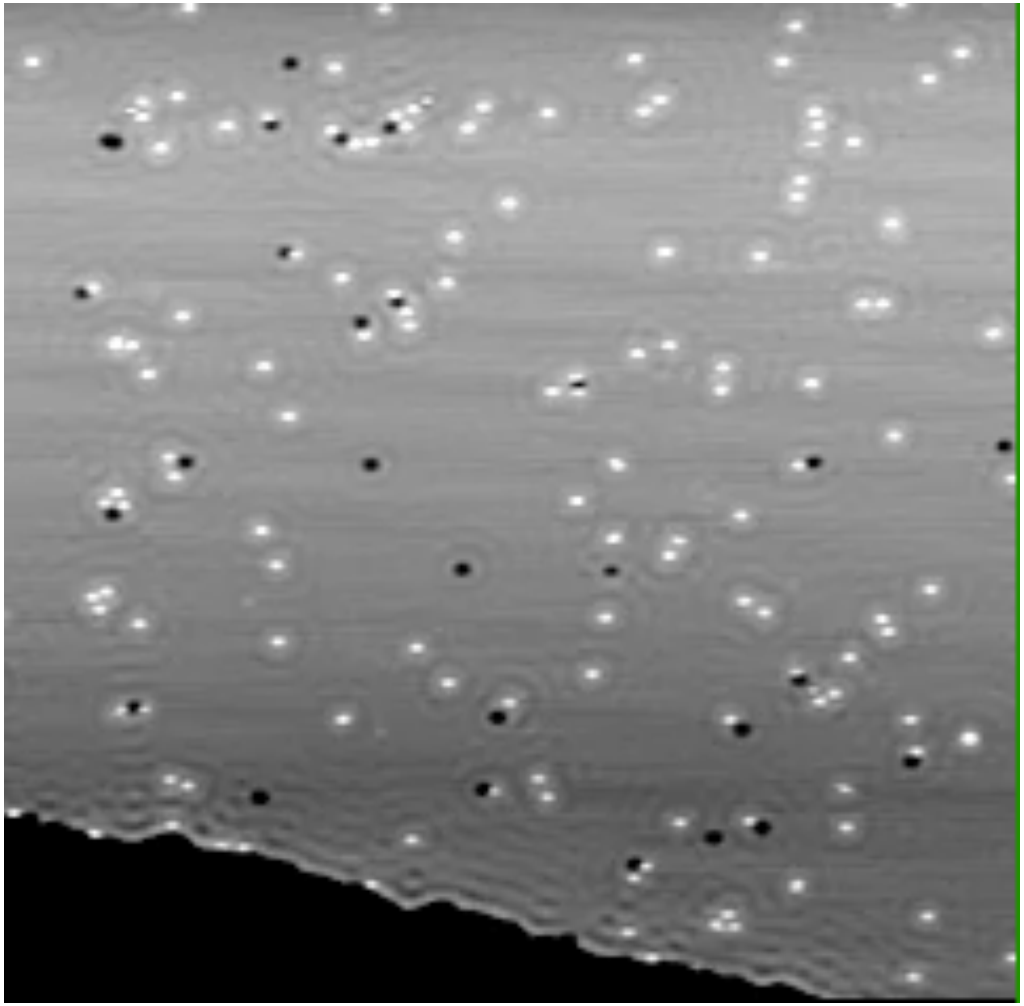


14 K

x 230
fast motion

30 nm x 32 nm

Brownian Motion



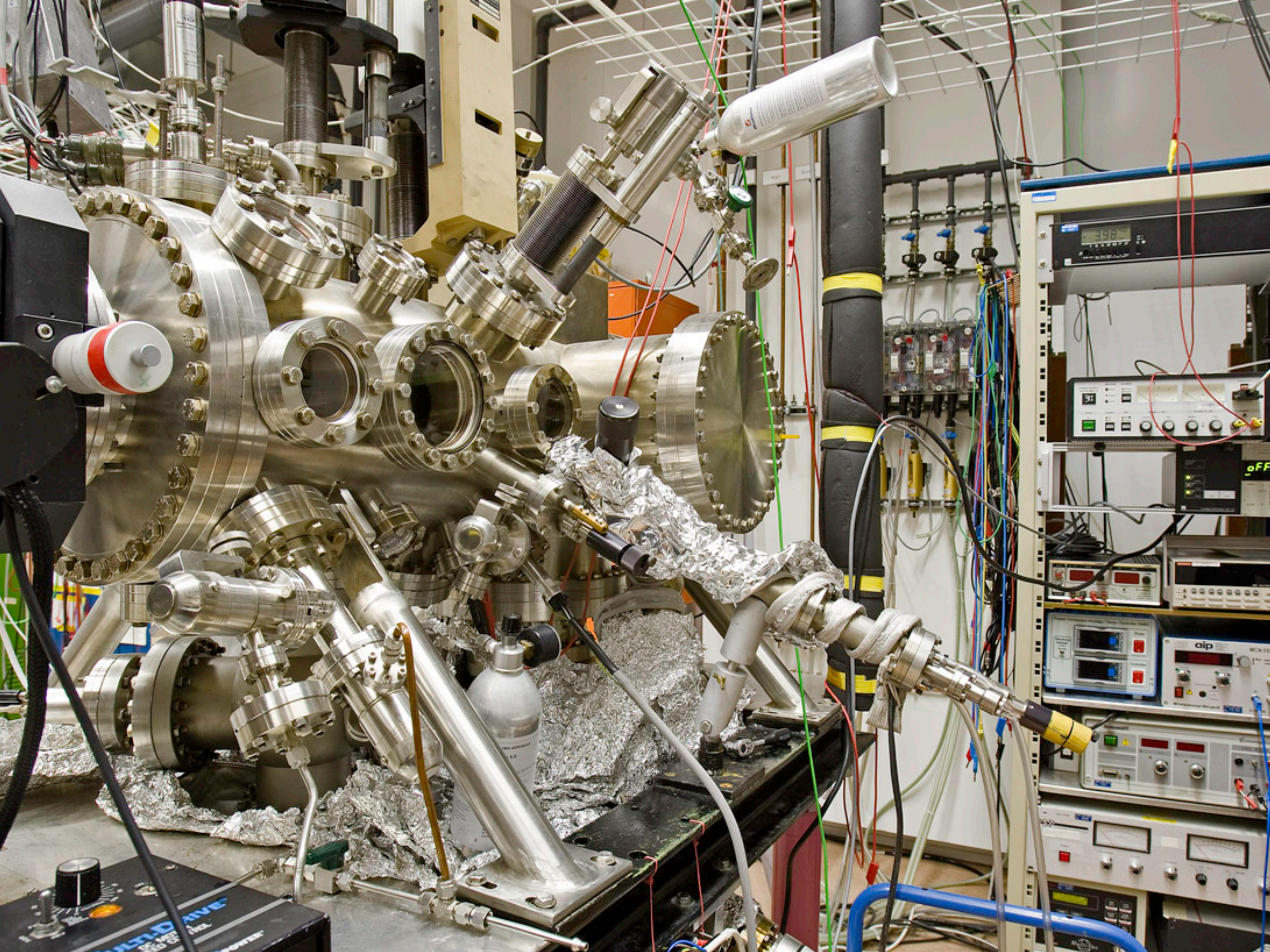
15 K

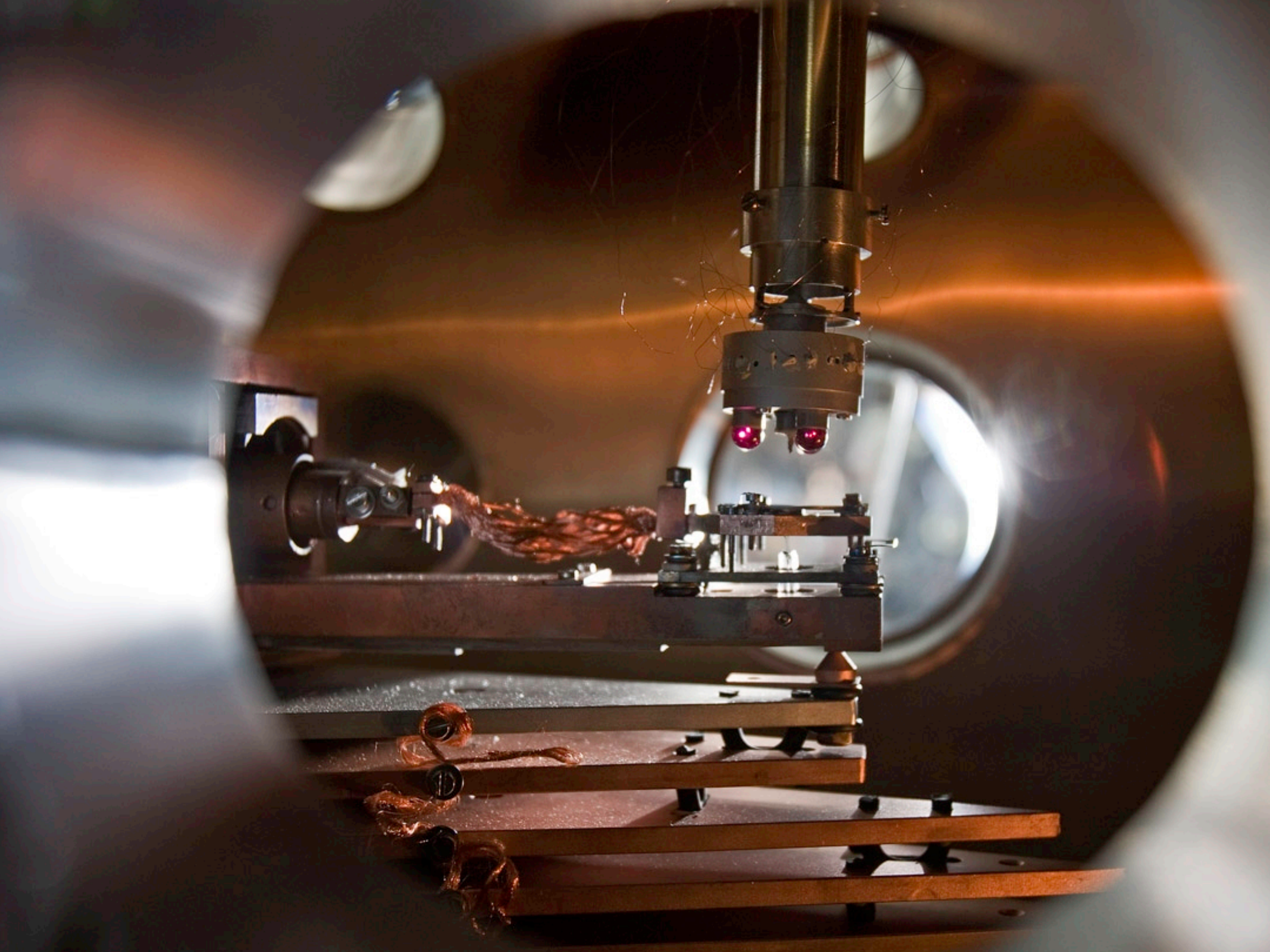
x 230
fast motion

60 nm x 60 nm

Brownian Motion ⇒ Einsteins most cited (1905) publication

Über die von der molekularkinetischen Theorie der Wärme
geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen."
Ann. Phys. **17**, 549 (1905)



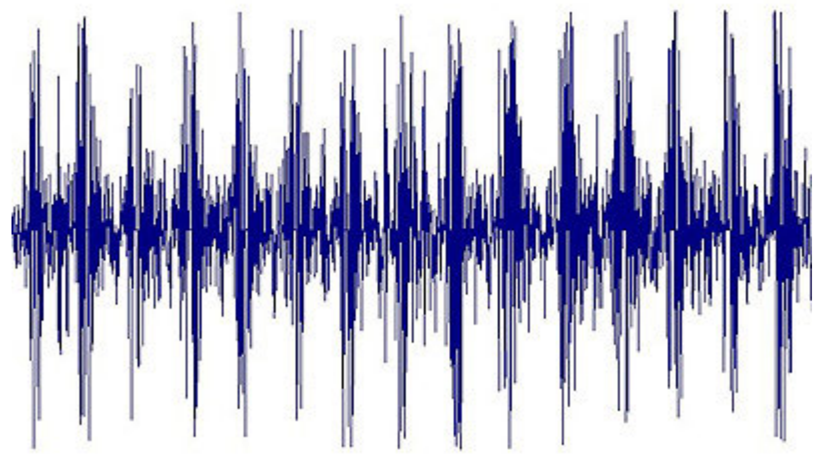


Artificial Earthquake

- 5 t synchronized Football Team

created by people at a football stadium

- Maximum Amplitude: **0,004 mm**

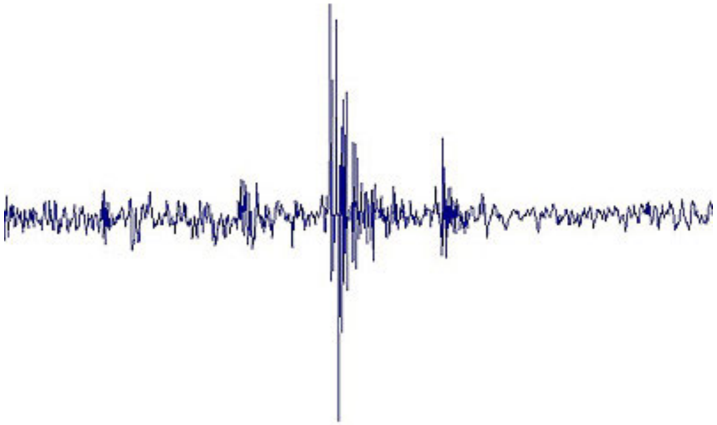


Artificial Earthquake

- One jump suffices

- Maximum Amplitude: 0,0005 mm

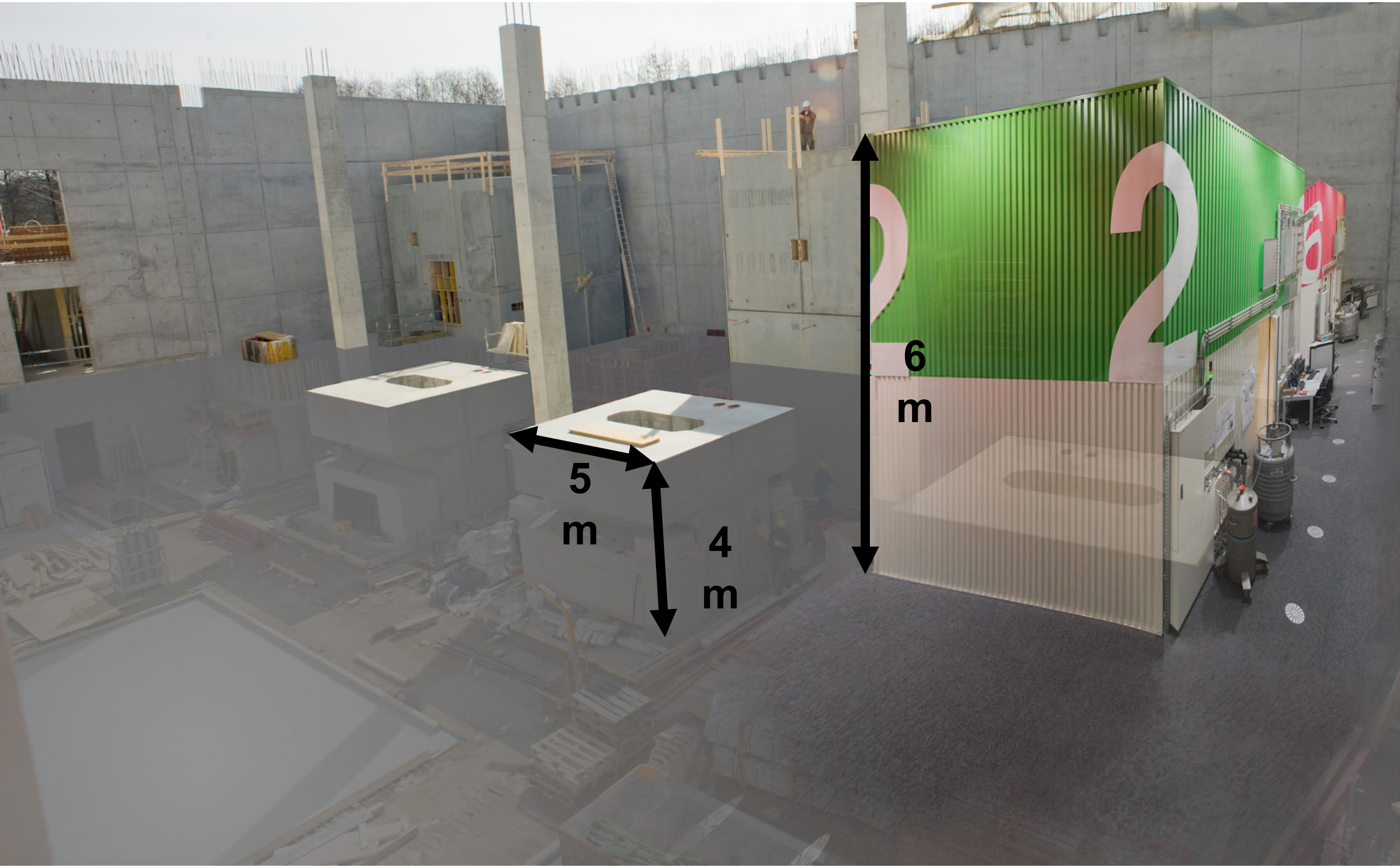
  = 500’000 Picometer !!!



Precision Laboratory at MPI Stuttgart

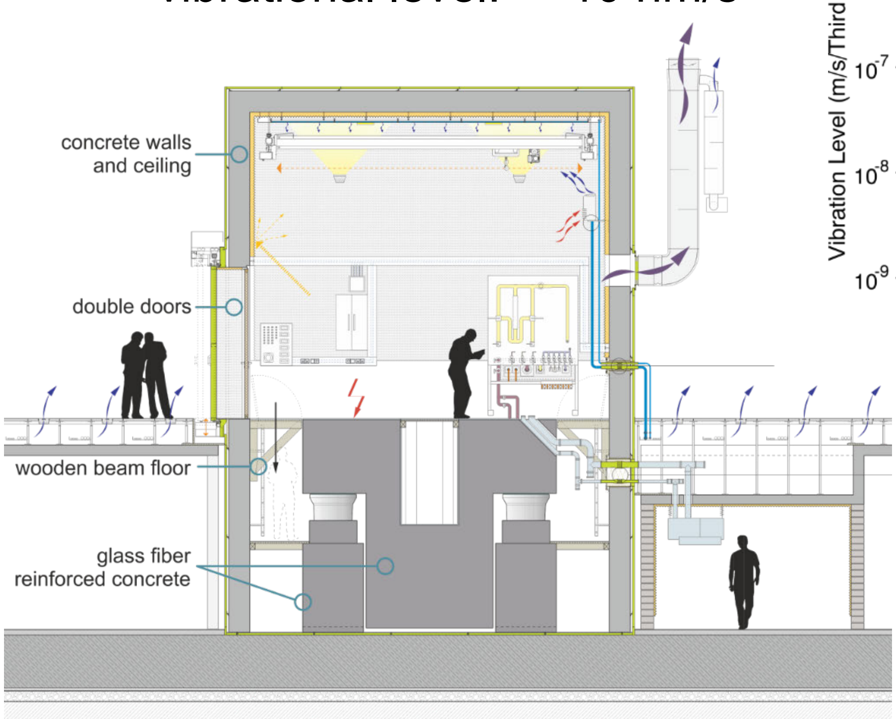
ultimate noise-free environment

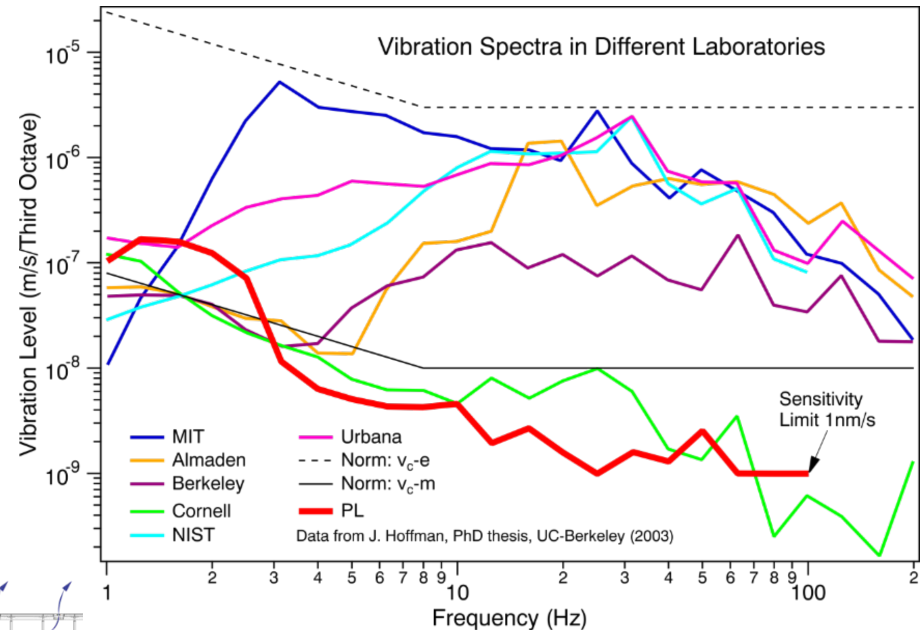
Precision Laboratory at MPI Stuttgart



Perfect Isolation in the Cube

vibrational level: < 10 nm/s



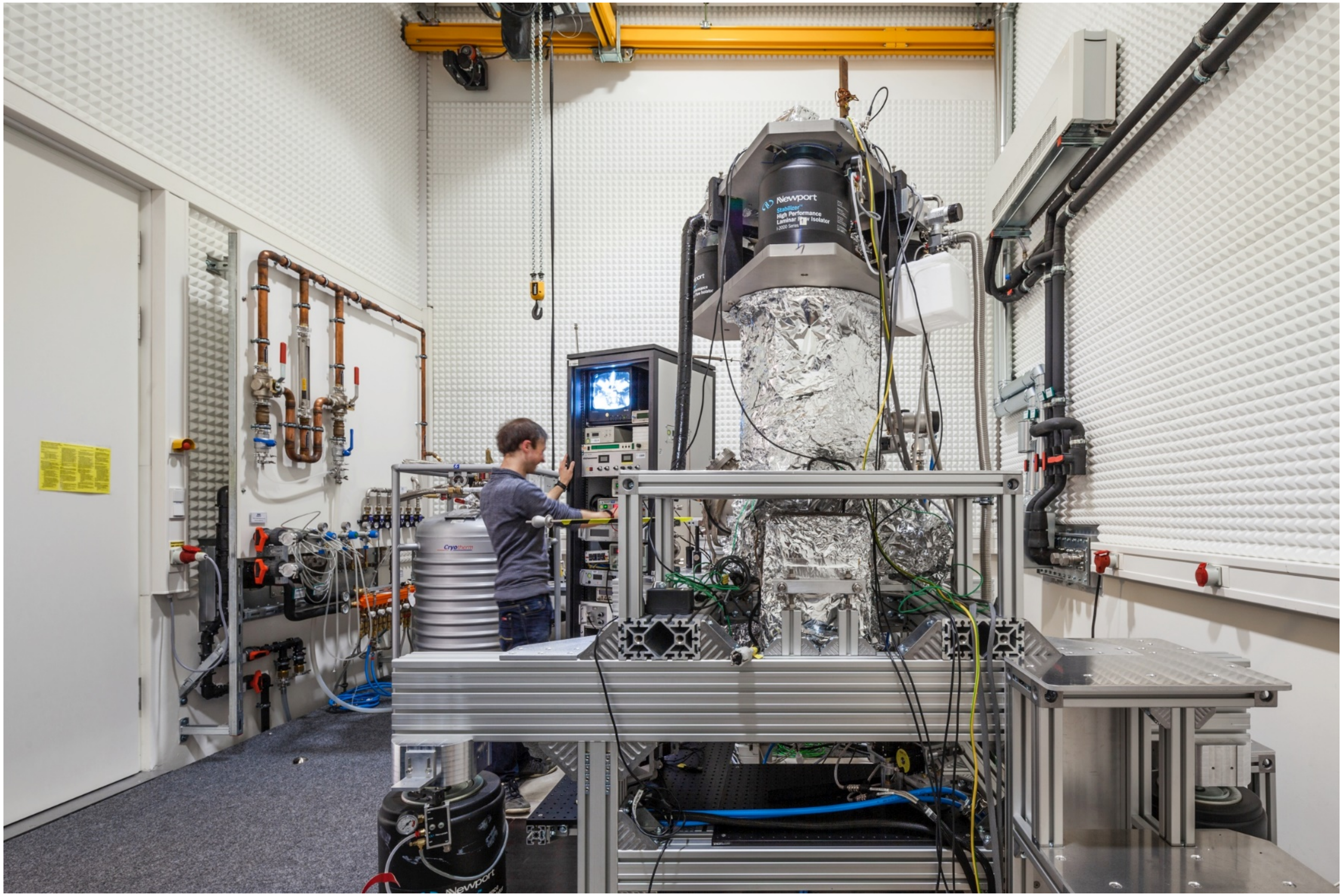


acoustic shielding: 60 dB

electromagnetic shielding: 60 – 100 dB

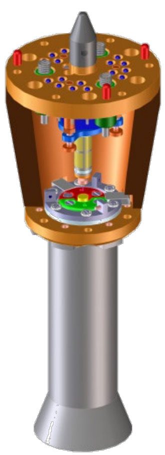
Manipulation and Spectroscopy of individual atoms, molecules, and nanostructures Transport measurements of quantum structures at ultra low temperatures and high magnetic fields.

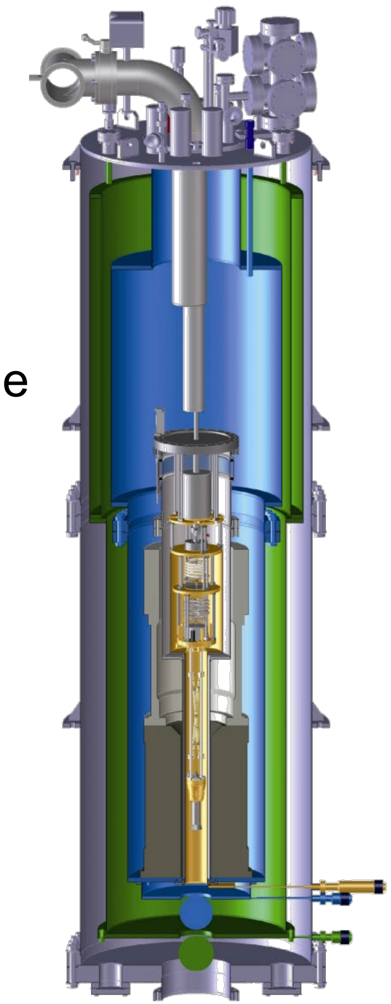
Quantum Measurements in the Cube



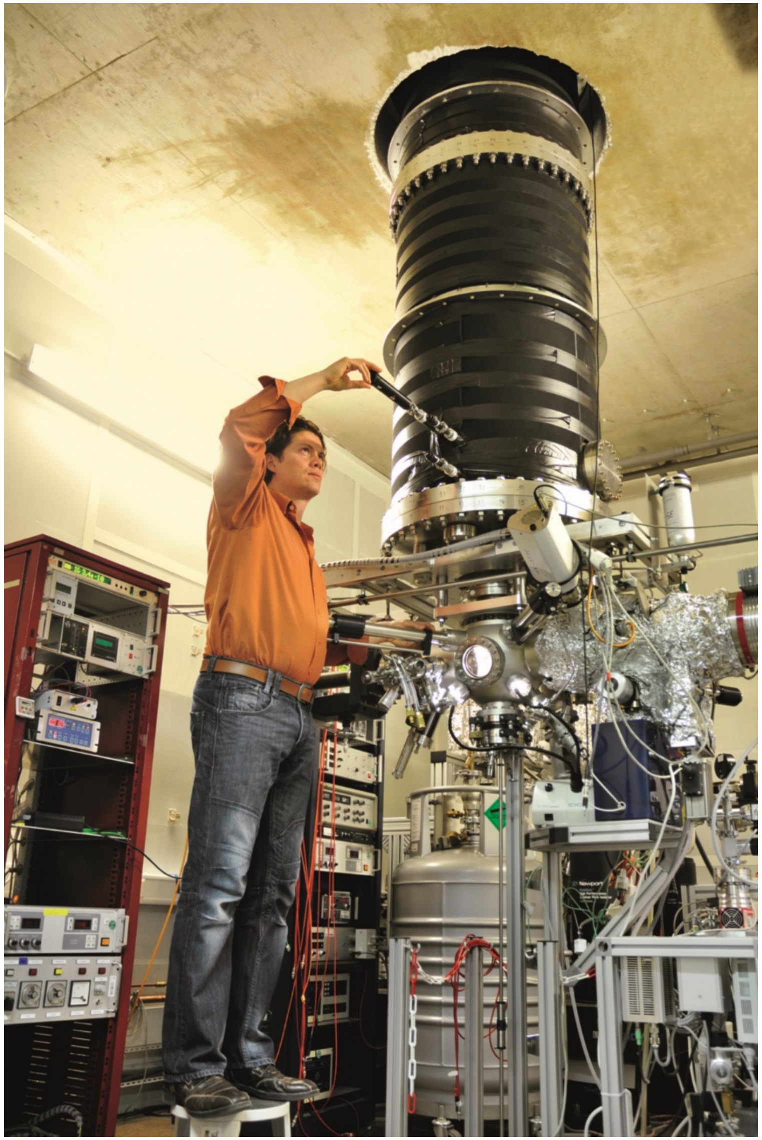
10 mK – 14 T – UHV **STM**

UHV compatible
dilution fridge





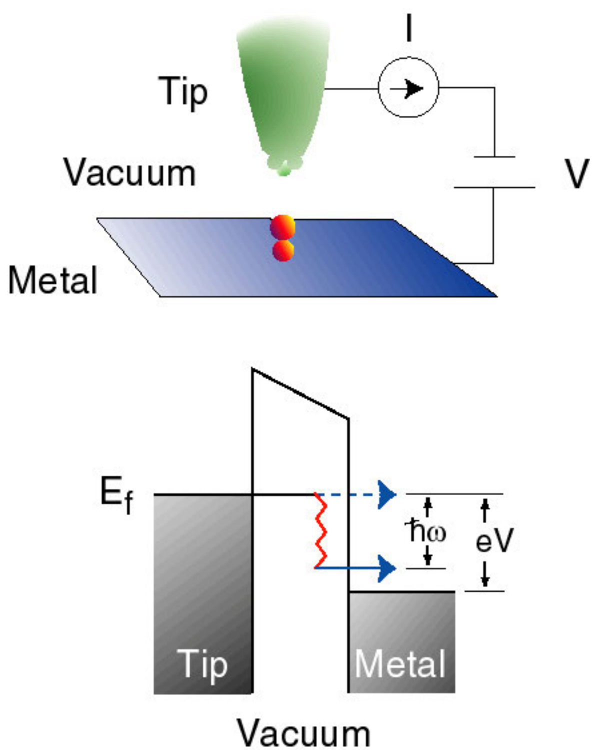
Energy Resolution
$\Delta E = 11.4 \pm 0.3 \mu eV$

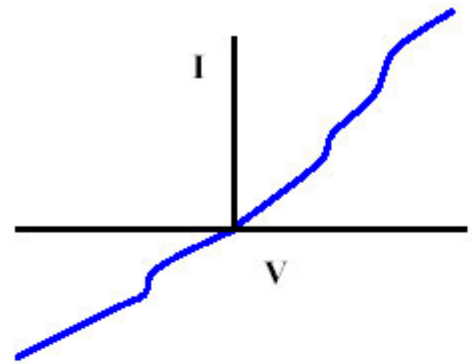


Rev. Sci. Instr. 84, 033903 (2013)

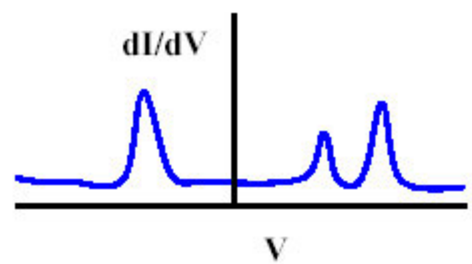
Spectroscopy of Single Molecules

Elastic vs. Inelastic Tunneling





$$I \sim e^{-\kappa z} \int_0^{eV} dE \cdot LDOS_{Sample}(E_F + E)$$

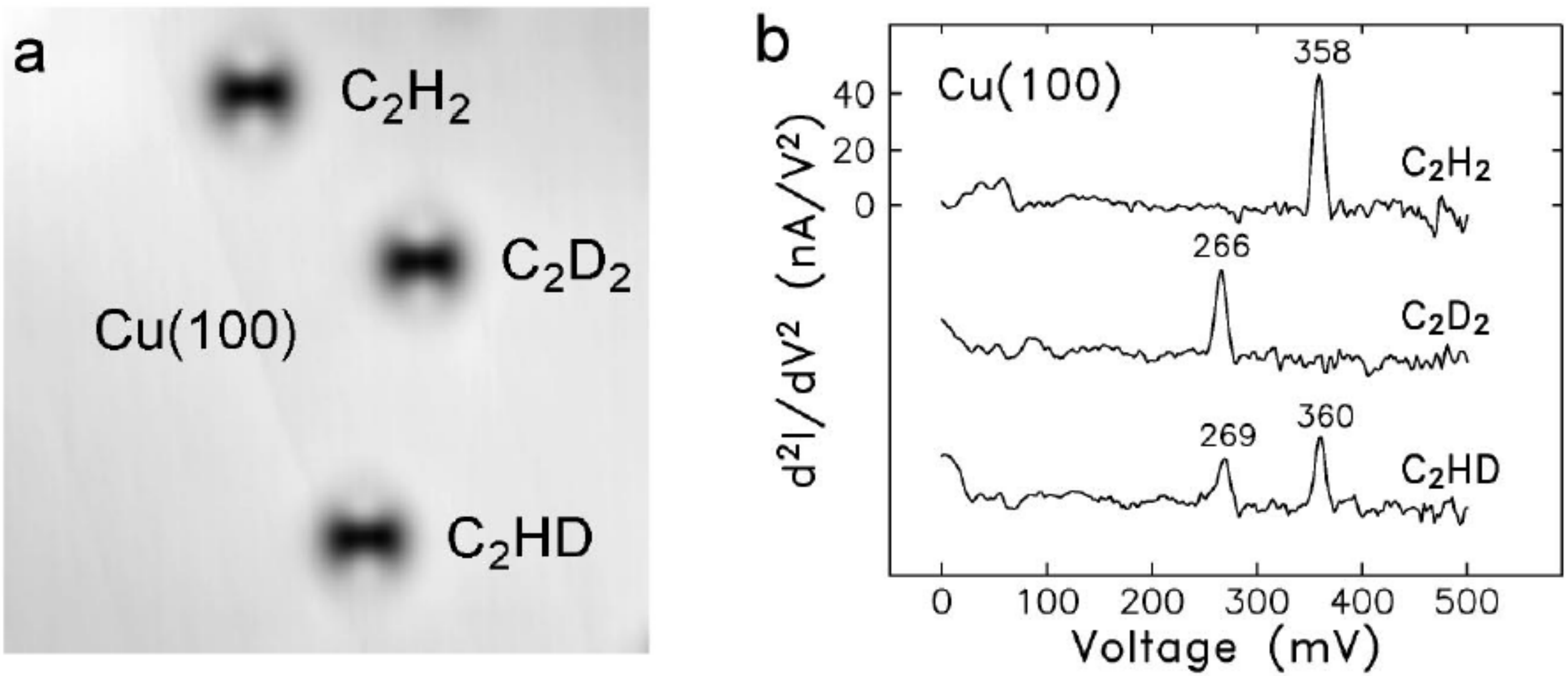


$$\left.\frac{dI}{dV}\right|_V \sim LDOS_{Sample}(E_F + eV)$$

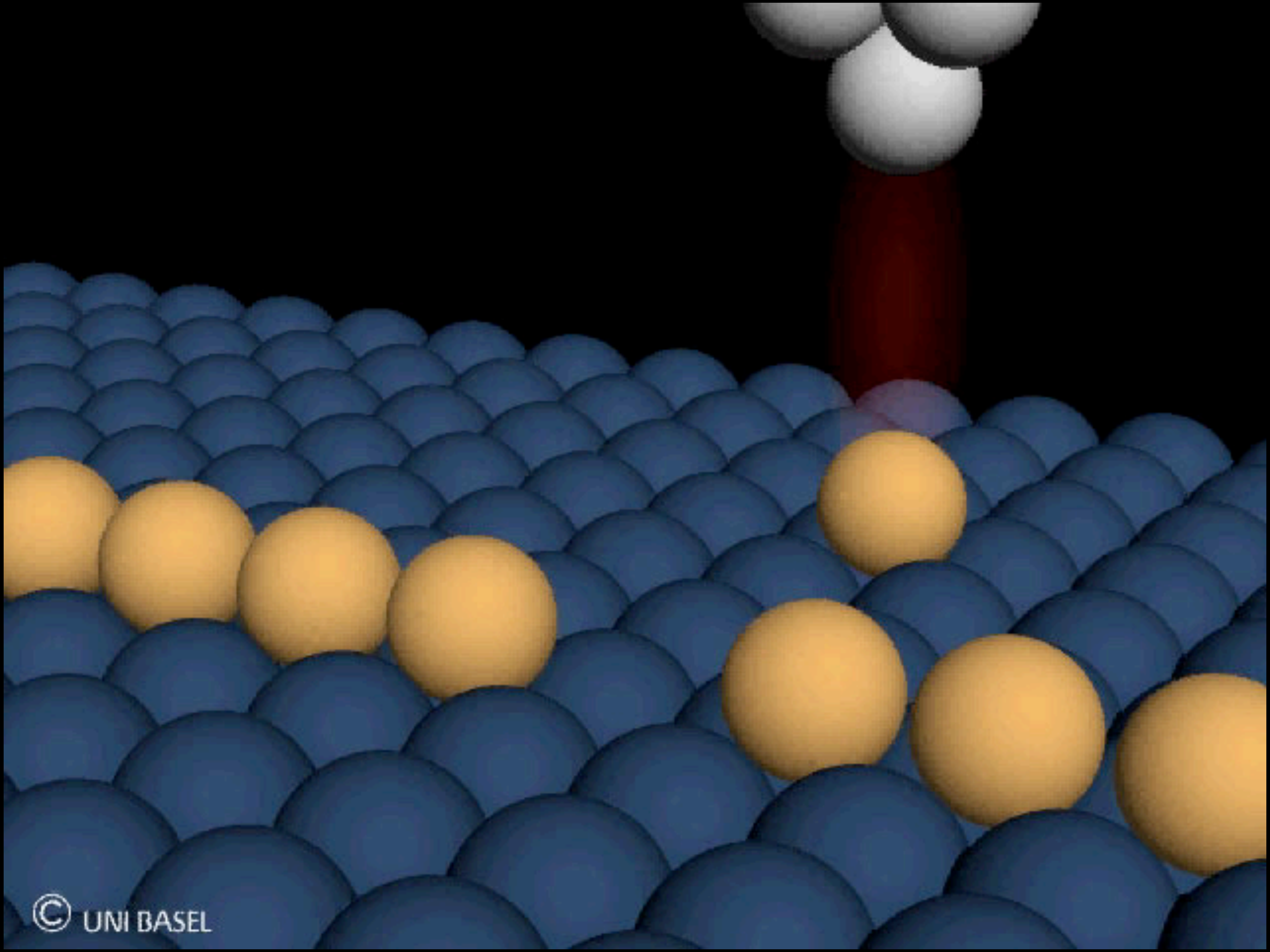
Keeping the tip of a scanning tunneling microscope (STM) at fixed position over the surface and sweeping the bias voltage, one can record a I-V characteristic. This technique is called scanning tunneling spectroscopy (STS). The first derivative gives information about the local density of states (LDOS) of the substrate, assuming that the tip has a constant density of states. The second derivative gives information on vibrations of the adsorbate as in IETS, which is why this technique is commonly called STM-IETS.

Vibrations of Single Molecules

Acetylen

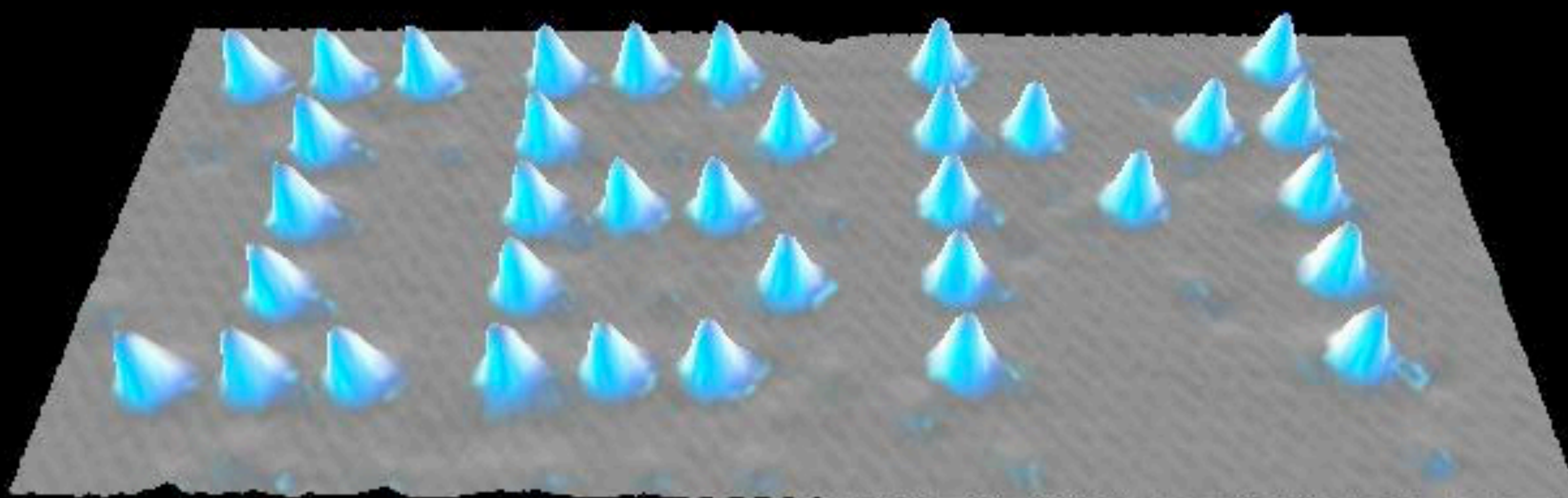


Beyond Imaging

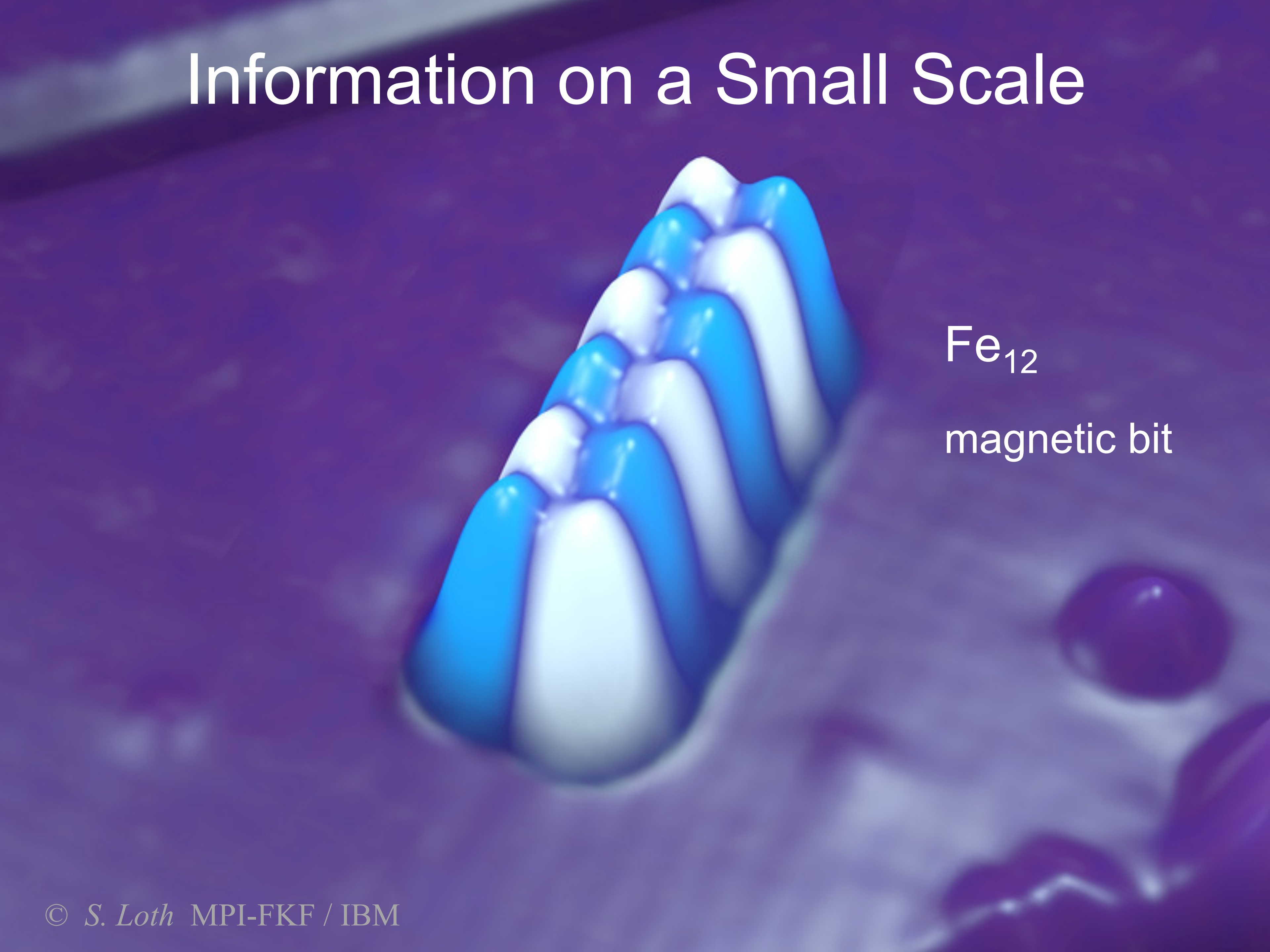


Rearranging the Atoms

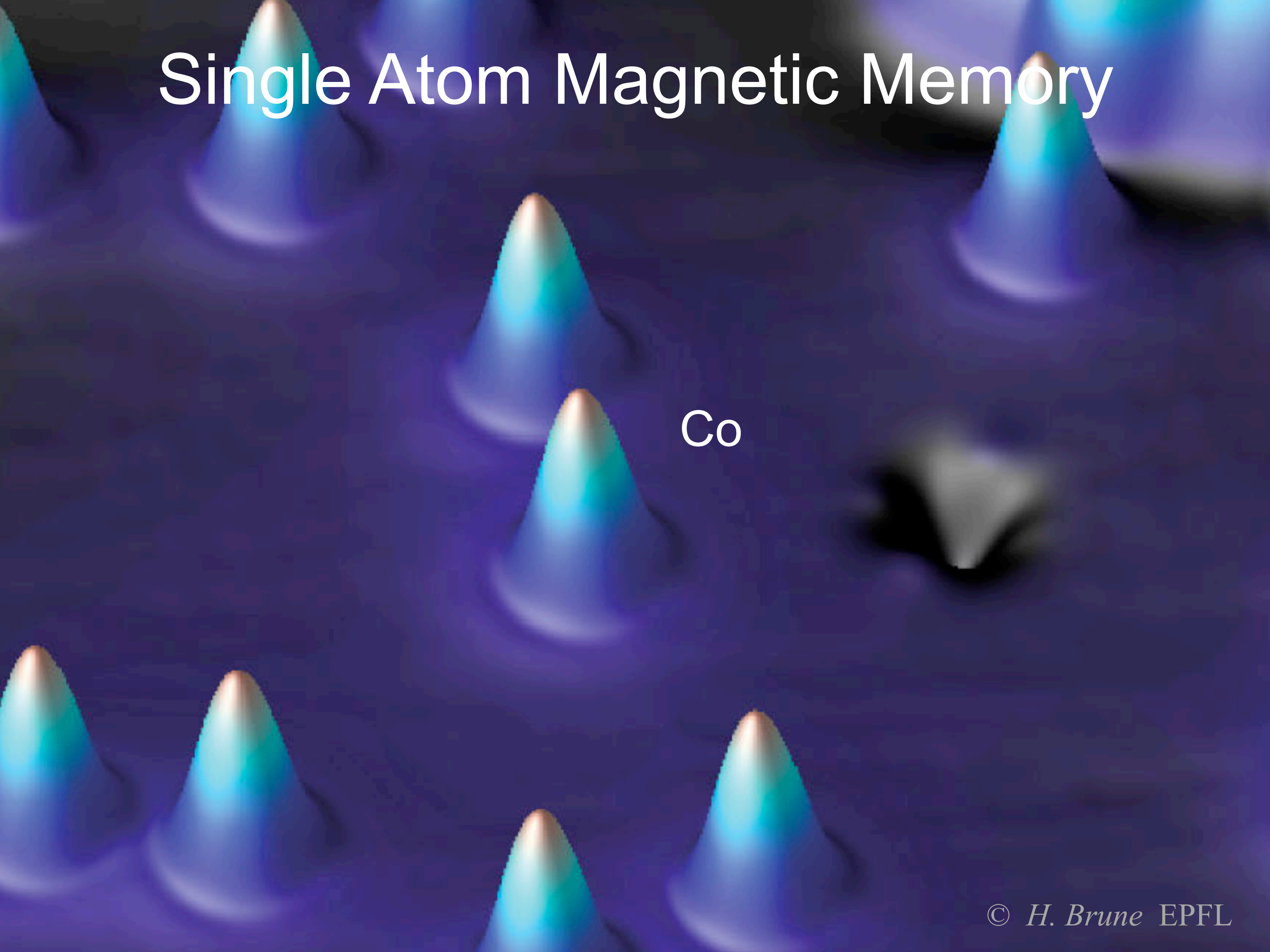
"But I am not afraid to consider the final question as to whether, ultimately – in the great future – we can arrange the atoms the way we want; the very atoms, all the way down!"



Information on a Small Scale

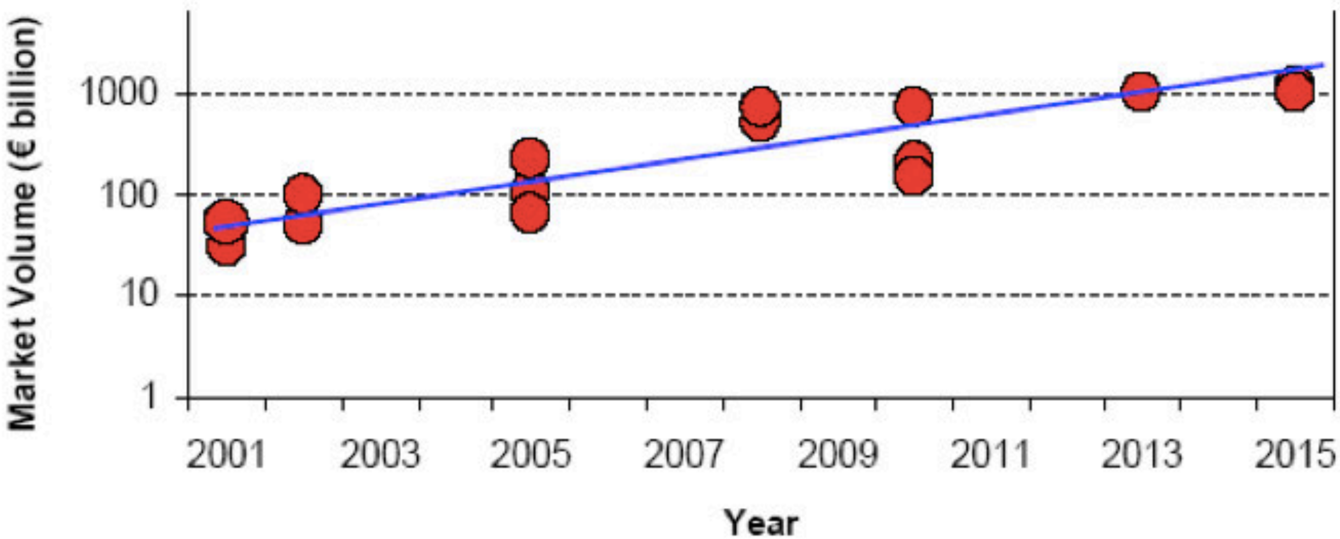


Single Atom Magnetic Memory

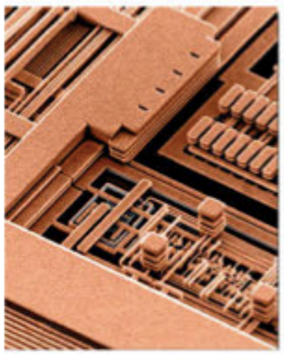


Nanotechnology:

Big Business?

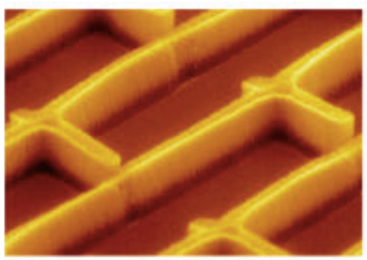


Nanotechnology: Applications

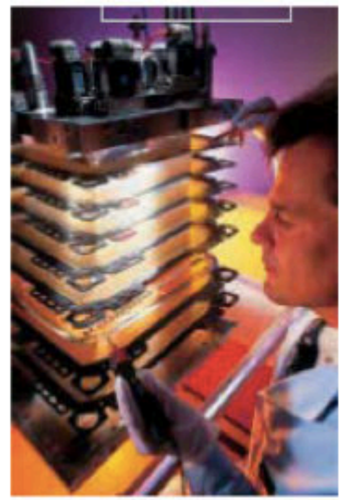


Information Technology

Instruments



Materials

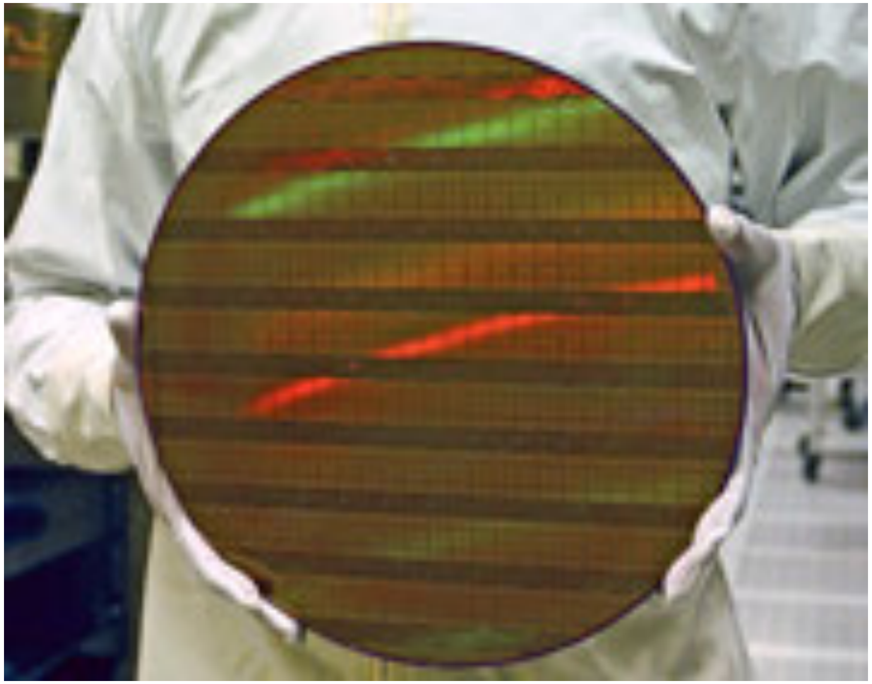


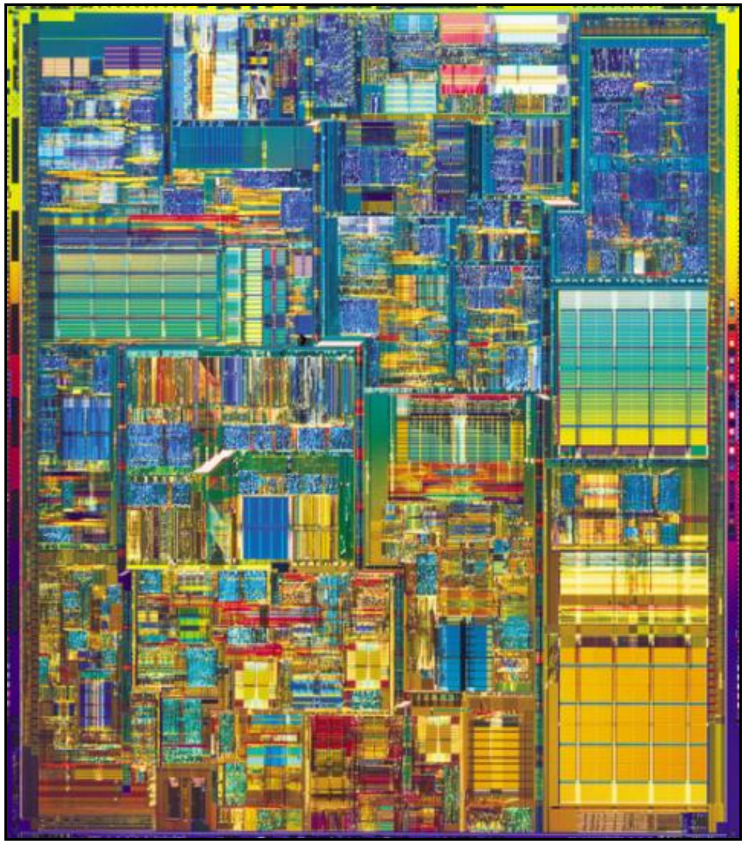
Energy

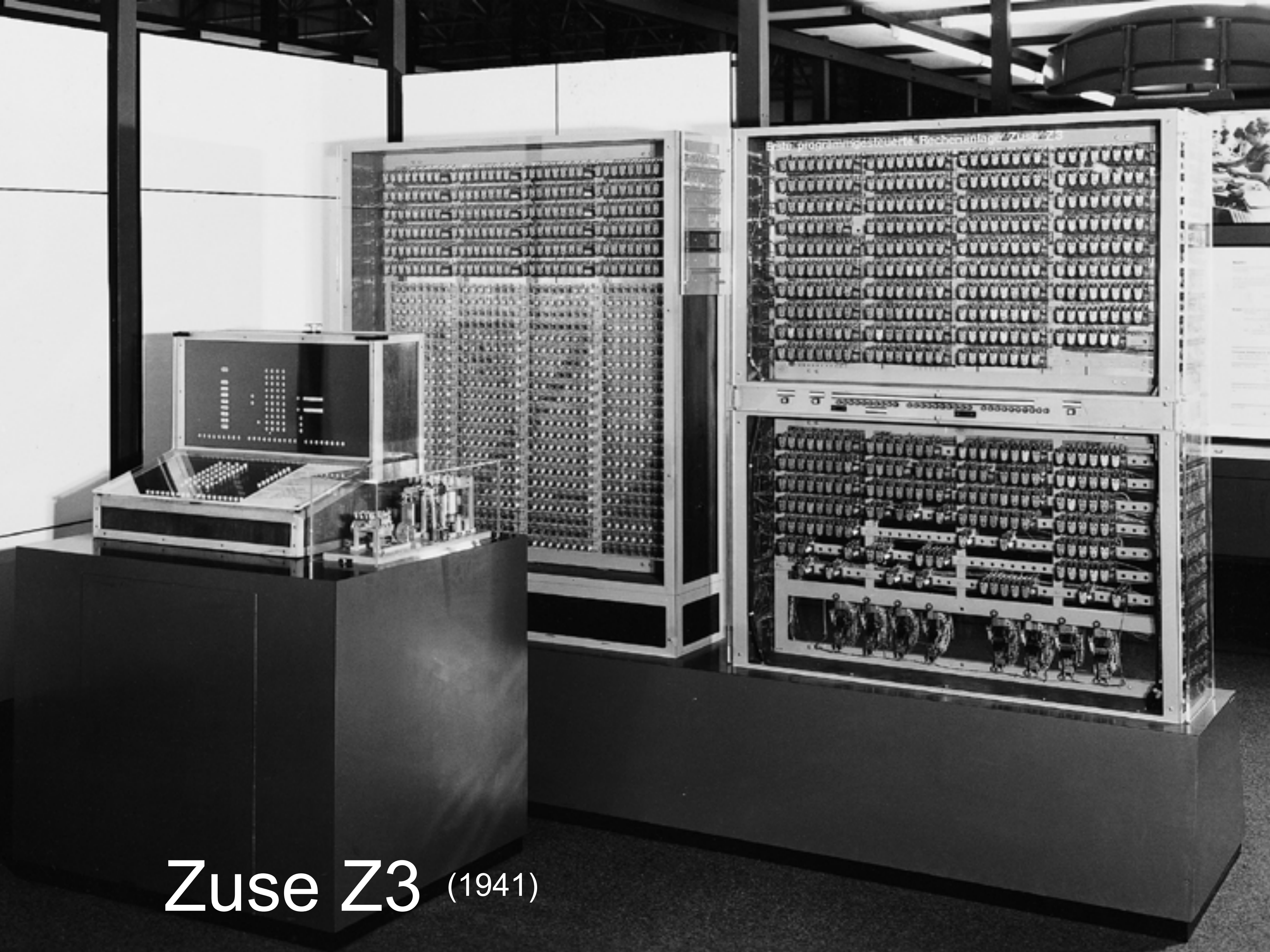
Environment

Medicine & Health

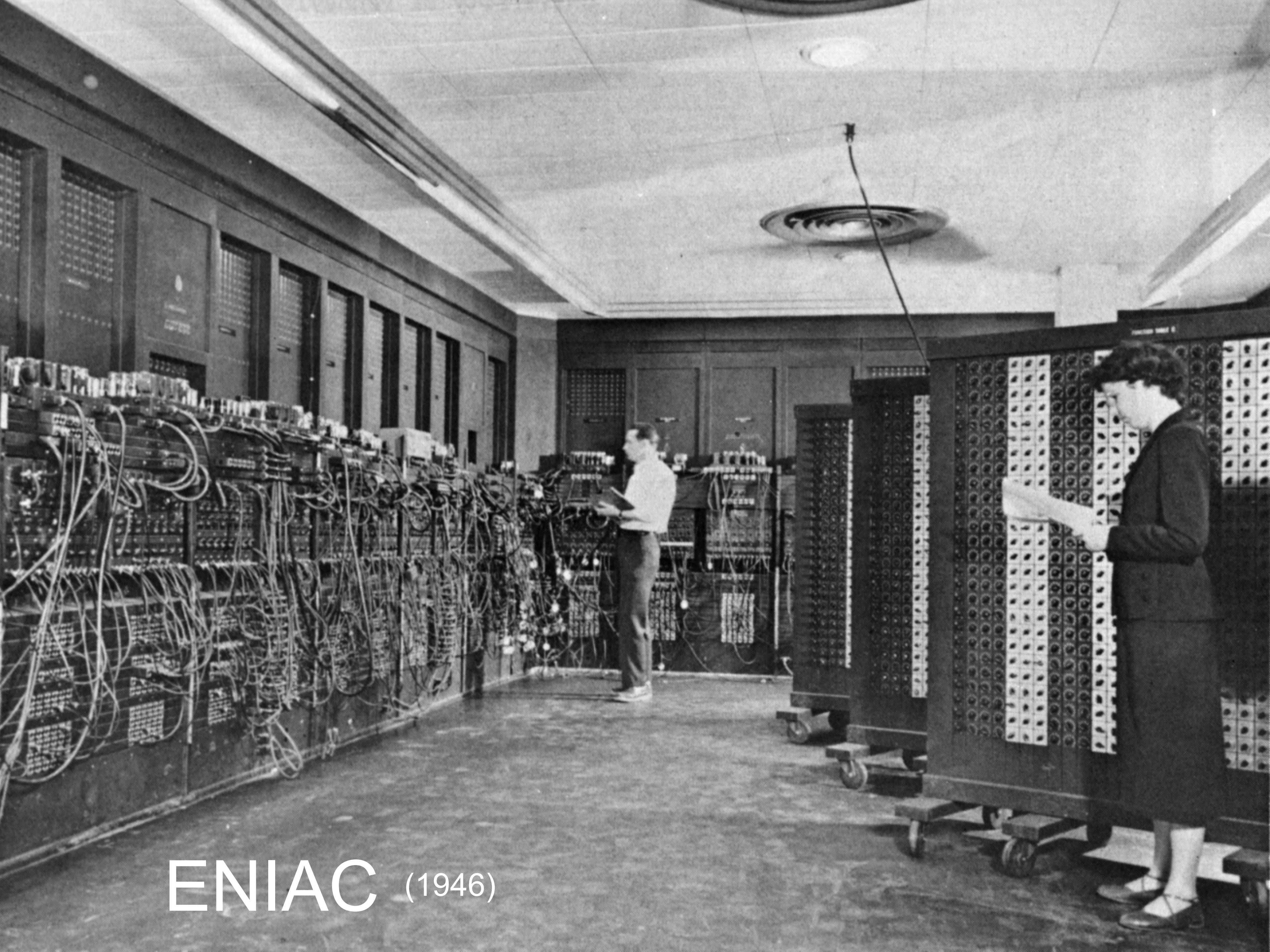
Computer Miniaturisation !!!!!!!!!

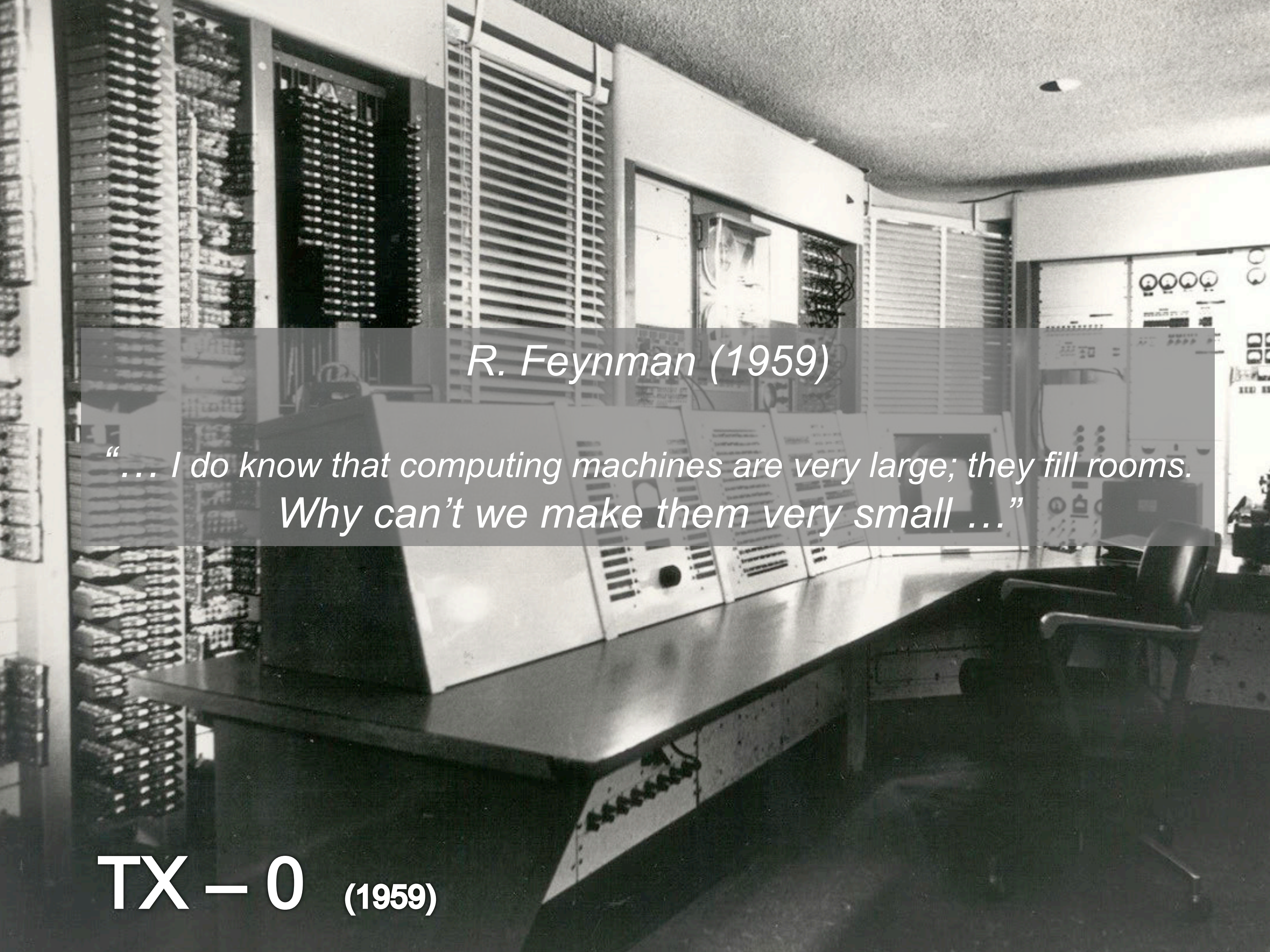


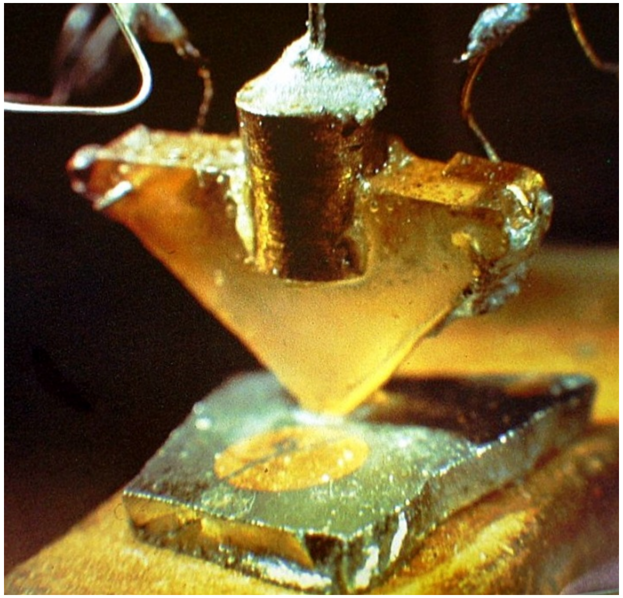


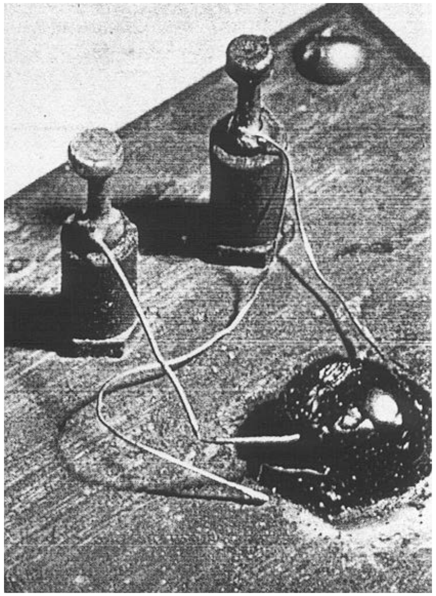


Zuse Z3 (1941)


ENIAC (1946)


R. Feynman (1959)
"… I do know that computing machines are very large; they fill rooms.
Why can't we make them very small …"
TX – 0 (1959)

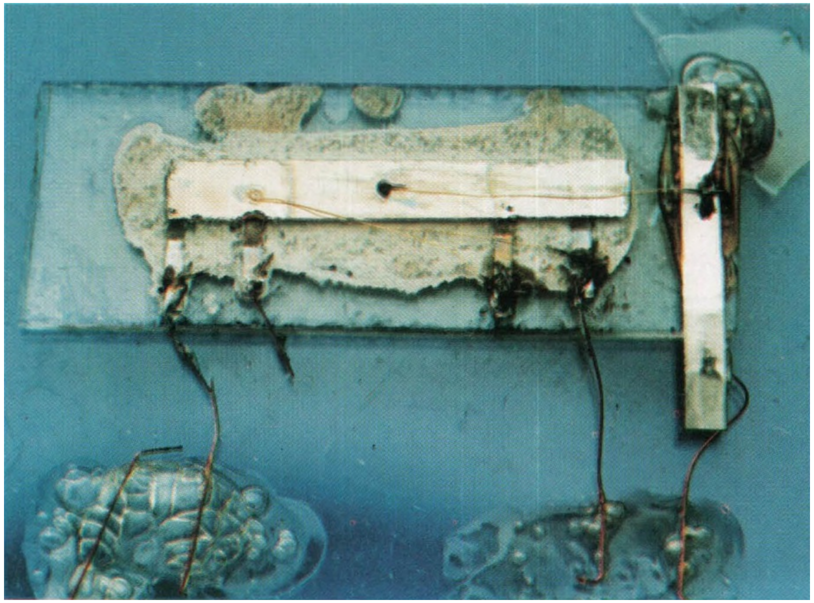




The first Transistor

Bardeen, Brattain &
Schockley

(1949)

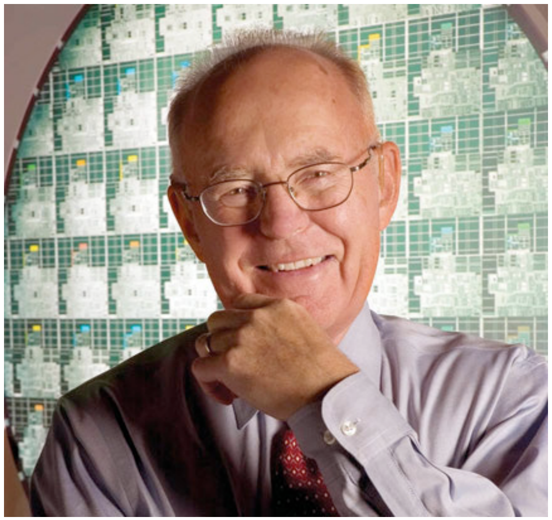


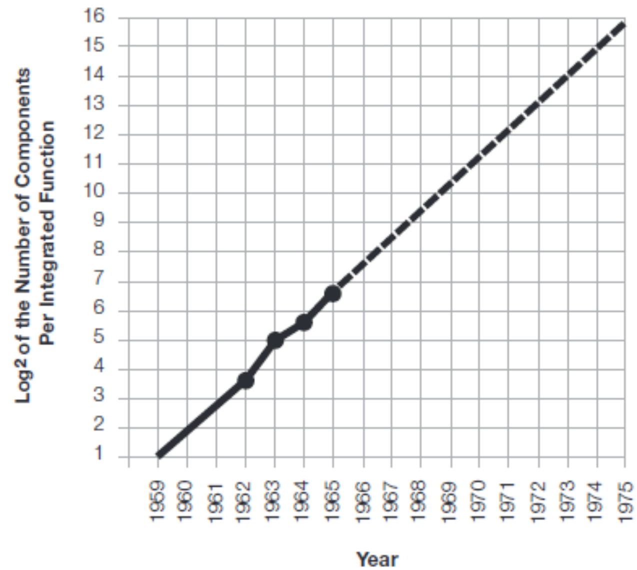
The first Integreated Circuit

Noyce & Kilby

(1958)

The incredible shrinking Transistor





Gordon E. Moore, Co-founder, Intel Corporation.

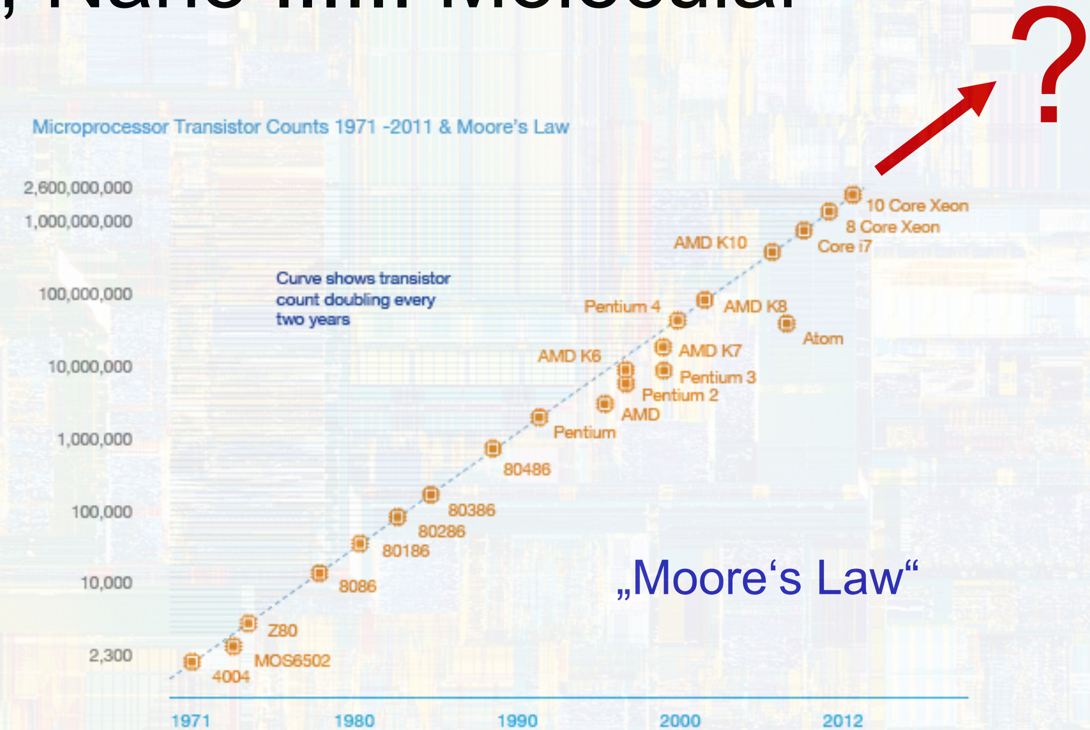
Electronics, Volume 38, Number 8, April 19, 1965

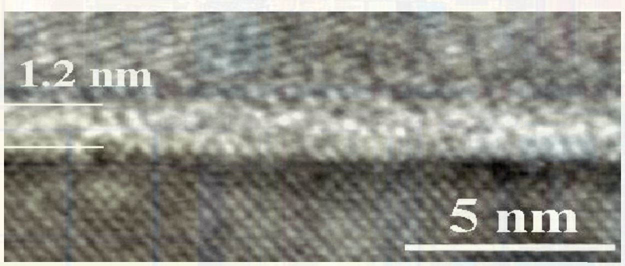
"With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip."

Moore's law is the observation that the number of transistors in a dense integrated circuit doubles approximately every two years.

Small, Micro, Nano ...... Molecular

14 nm 2nd Generation
Tri-gate Transistor

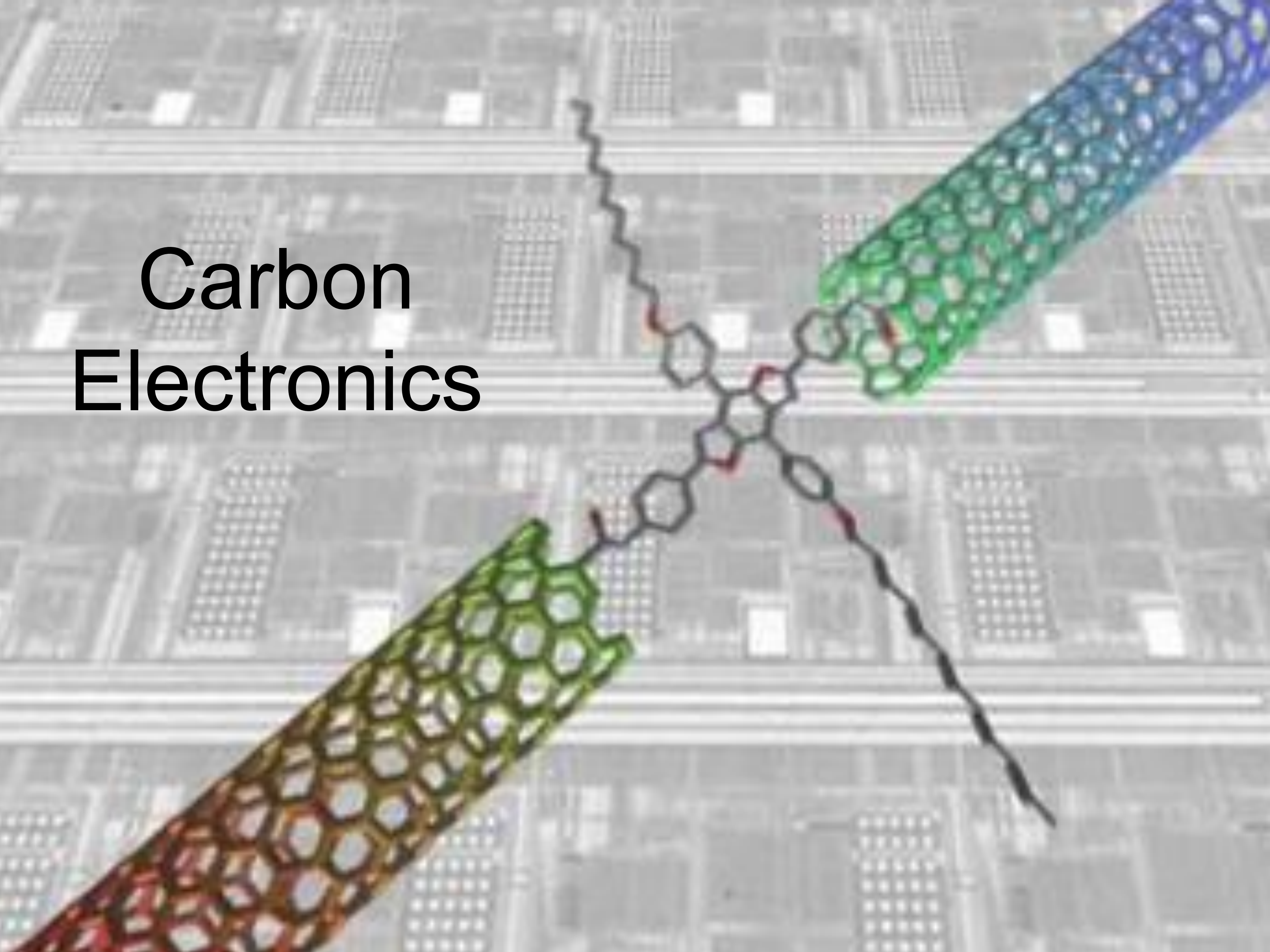




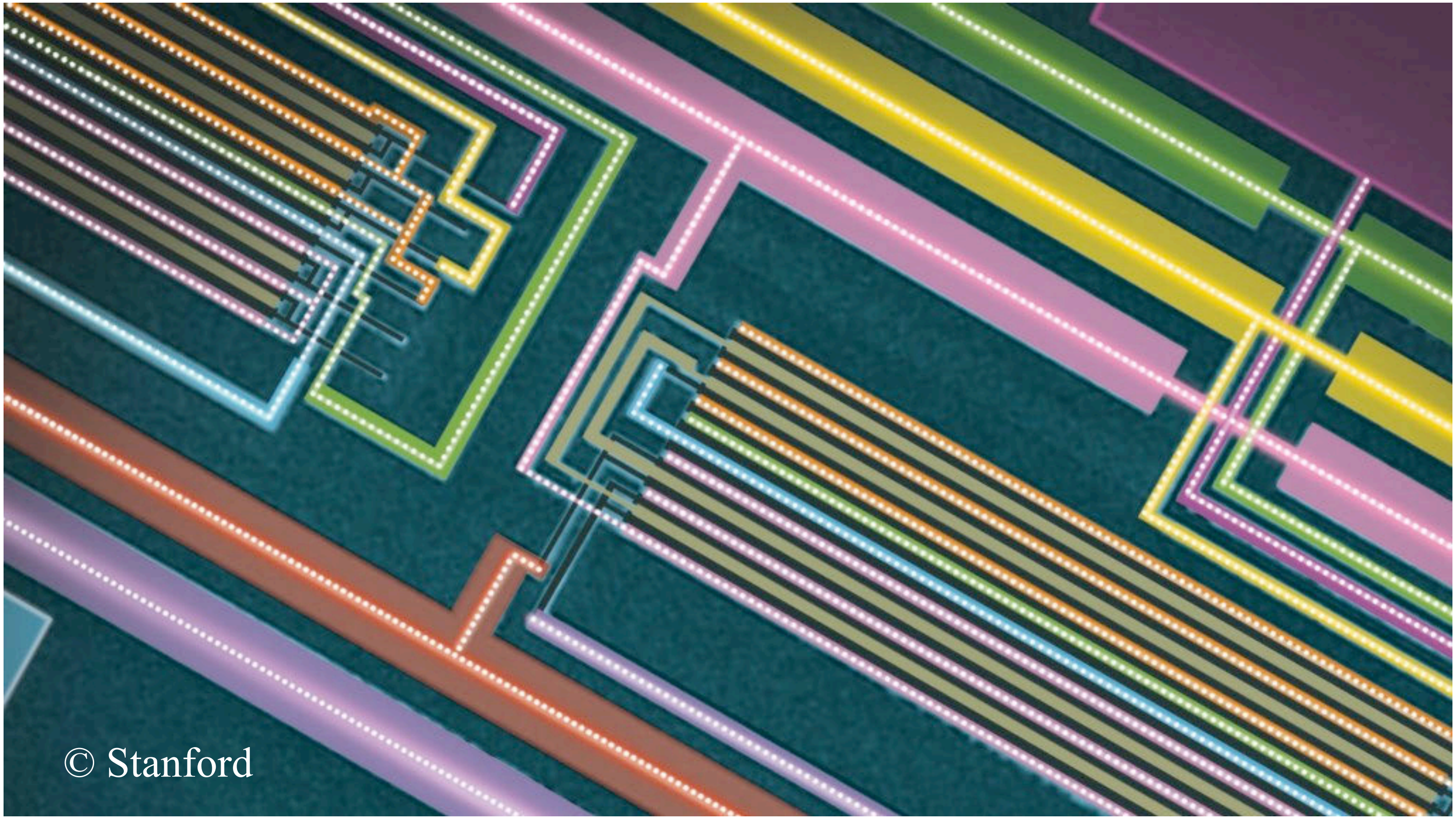
TEM image of SiO_2 Barrier

Ultimate Scale :
Molecular Dimensions

Carbon Electronics

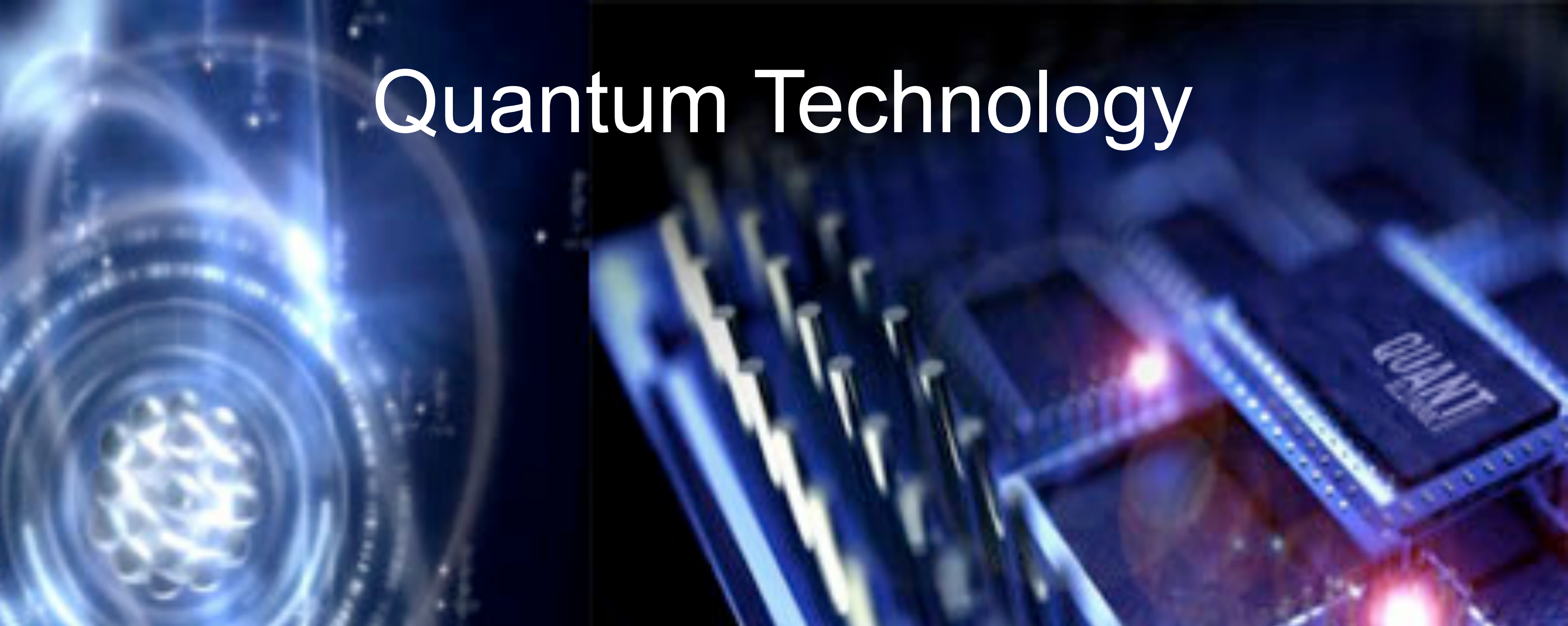


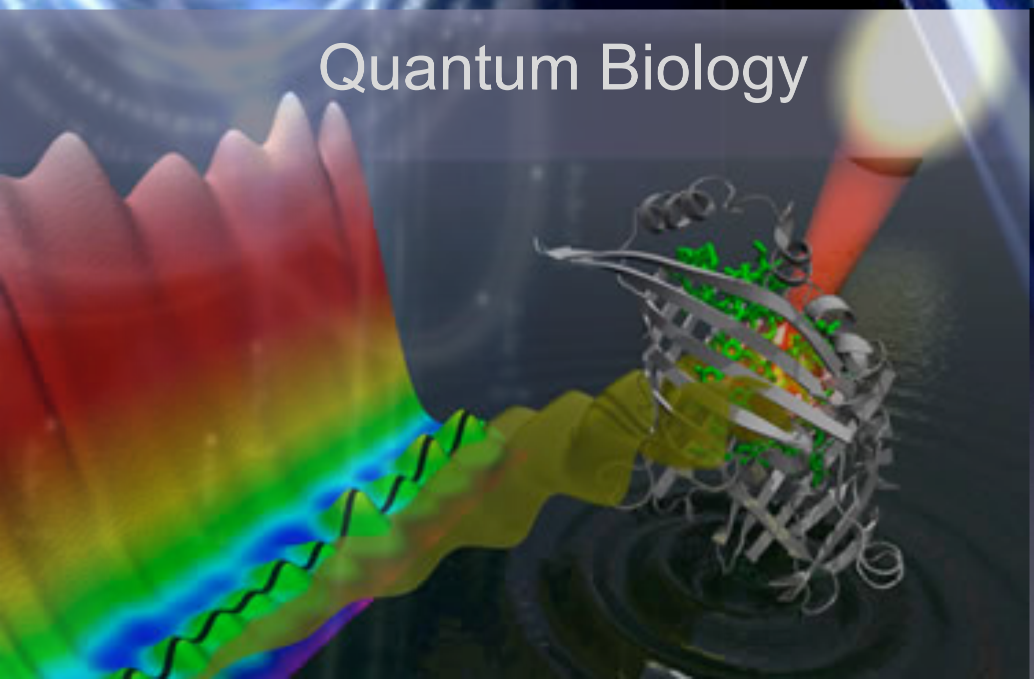
Carbon Nanotube Computer



142 transistor computer – Turing complete

Quantum Technology

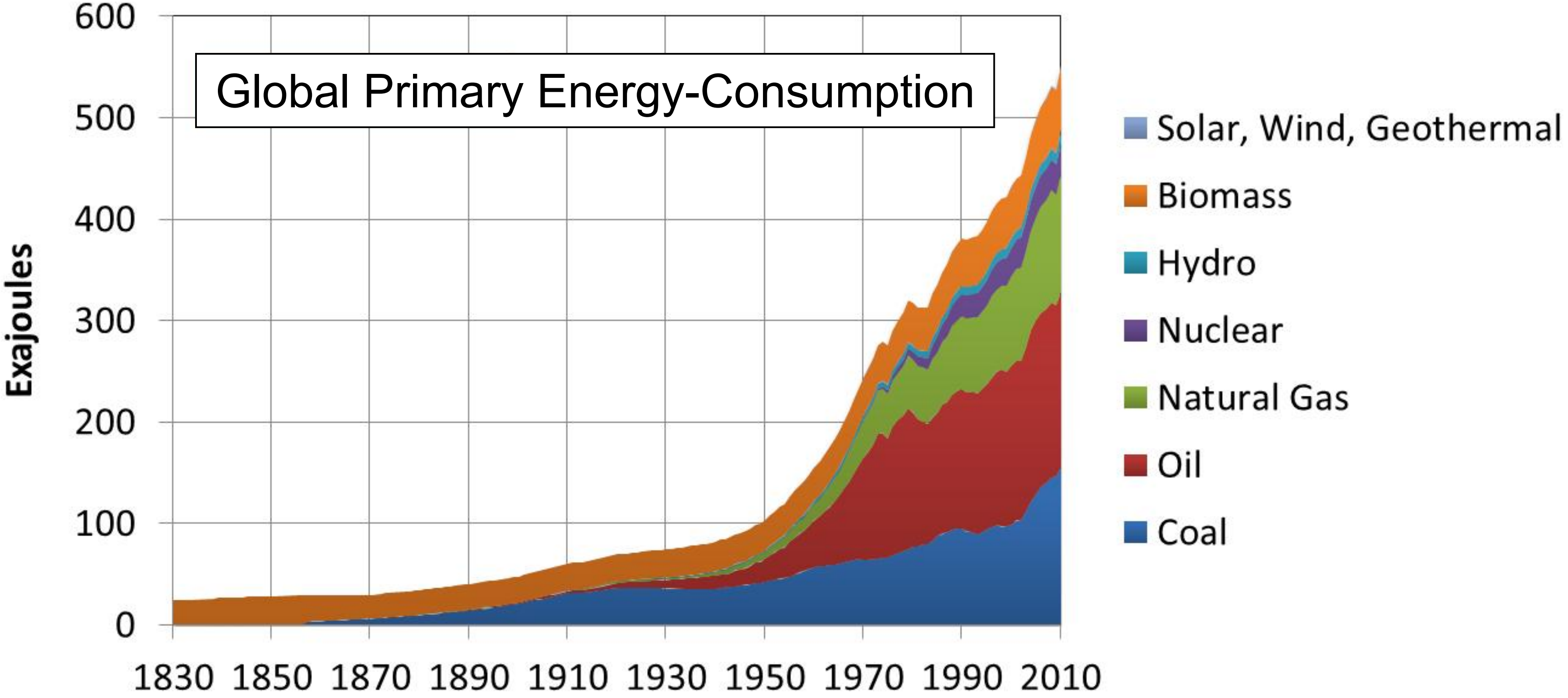




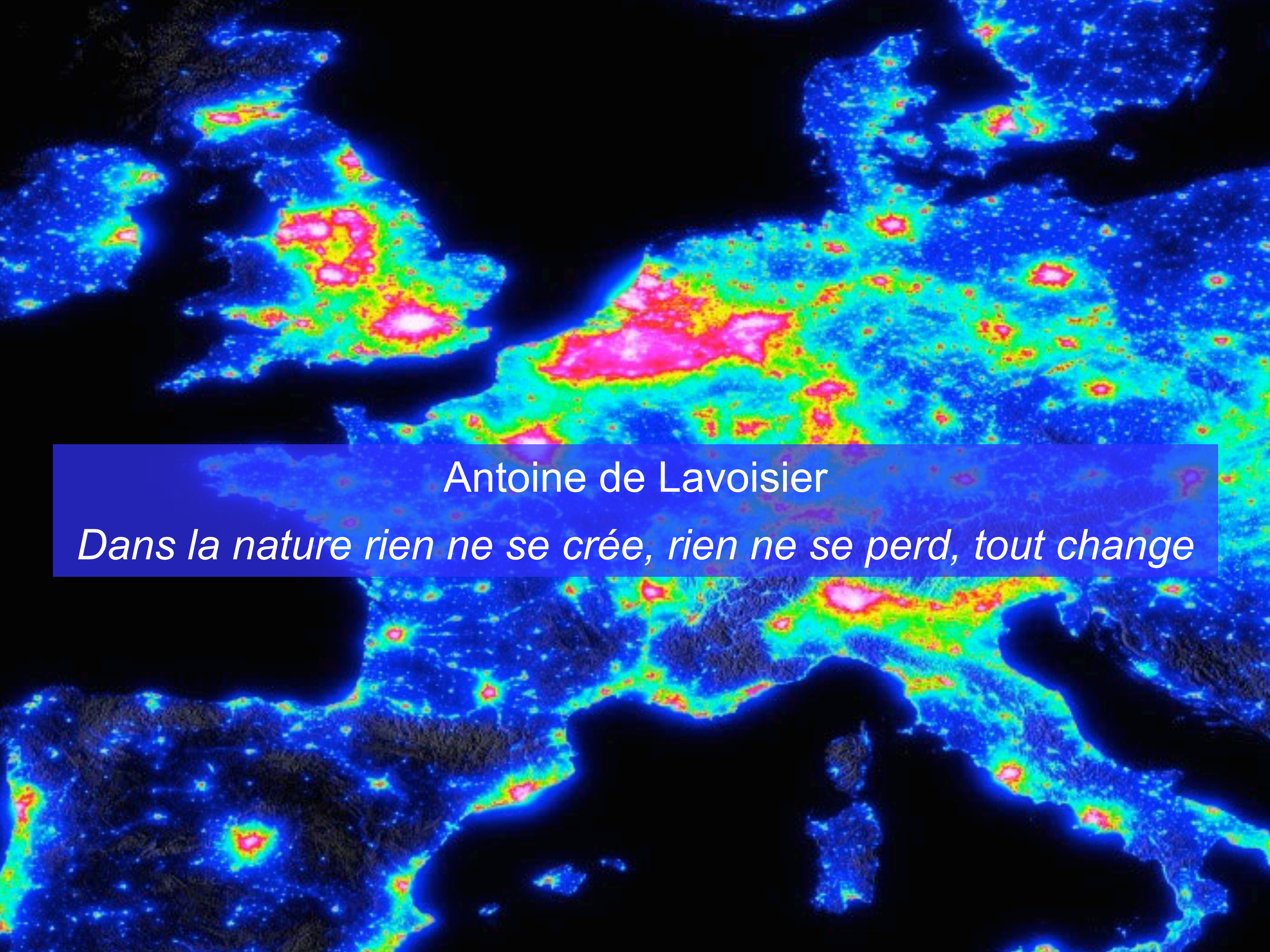
Bits, Pbits, Qubits

	bit	probabilistic bit	quantum bit
Configurations:	0 1	0 1	0 1
Description:	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} p \\ 1-p \end{bmatrix}$ $p \in \mathbb{R}$	$\begin{bmatrix} \alpha \\ \beta \end{bmatrix}$ $\alpha, \beta \in \mathbb{C}$
Observation:	0 certainty	0 *p* percent 1 *1-p* percent	0 $\lvert\alpha\rvert^2$percent 1 $\lvert\beta\rvert^2$percent
Evolution:	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ deterministic	$\begin{bmatrix} 1-q & r \\ q & 1-r \end{bmatrix}$ stochastic	$\begin{bmatrix} u & v \\ w & x \end{bmatrix}$ unitary

Energy !!!!!


Global Primary Energy-Consumption
Exajoules
600
500
400
300
200
100
0
1830 1850 1870 1890 1910 1930 1950 1970 1990 2010
Solar, Wind, Geothermal
Biomass
Hydro
Nuclear
Natural Gas
Oil
Coal

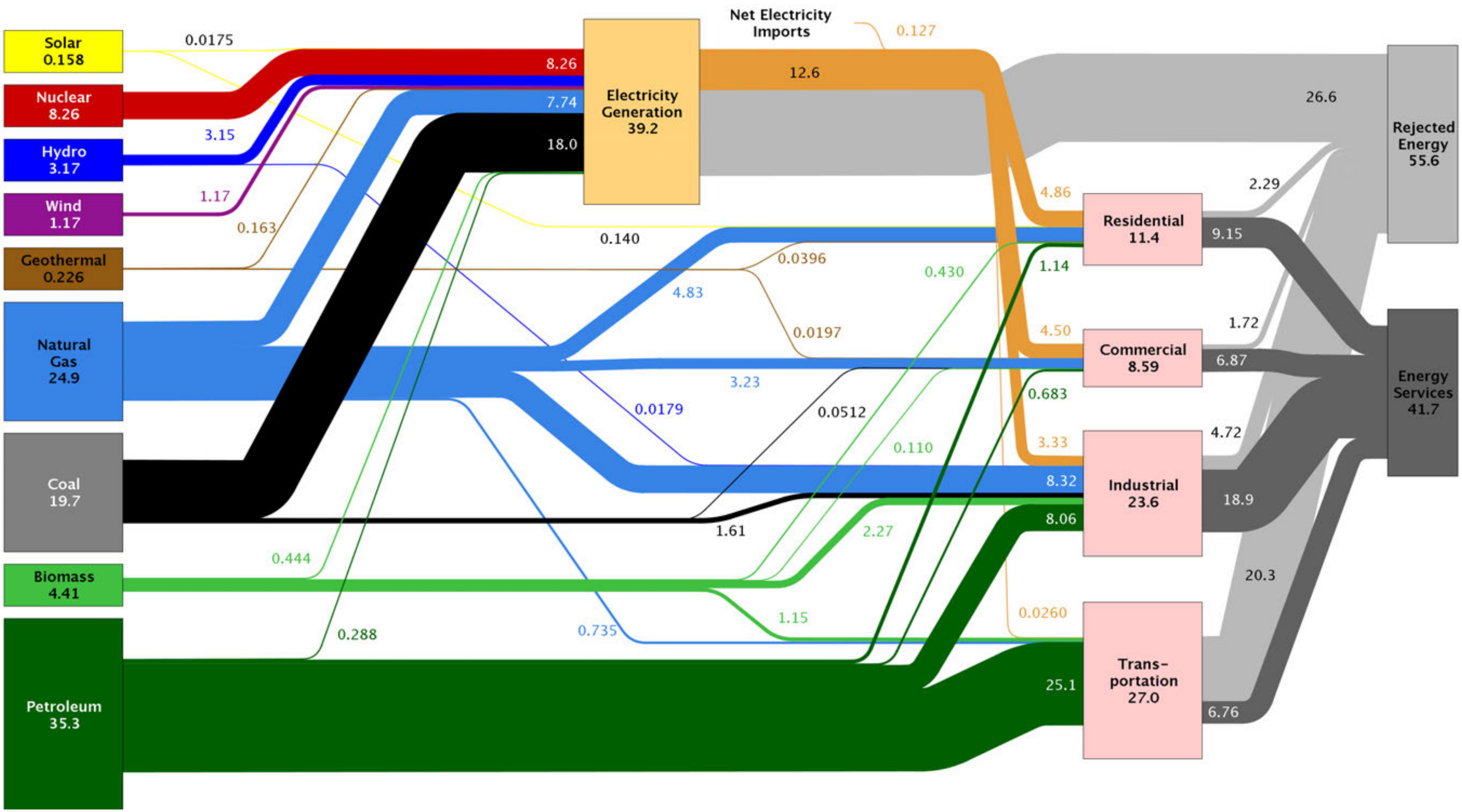

Sustainable Energy Supply



Antoine de Lavoisier

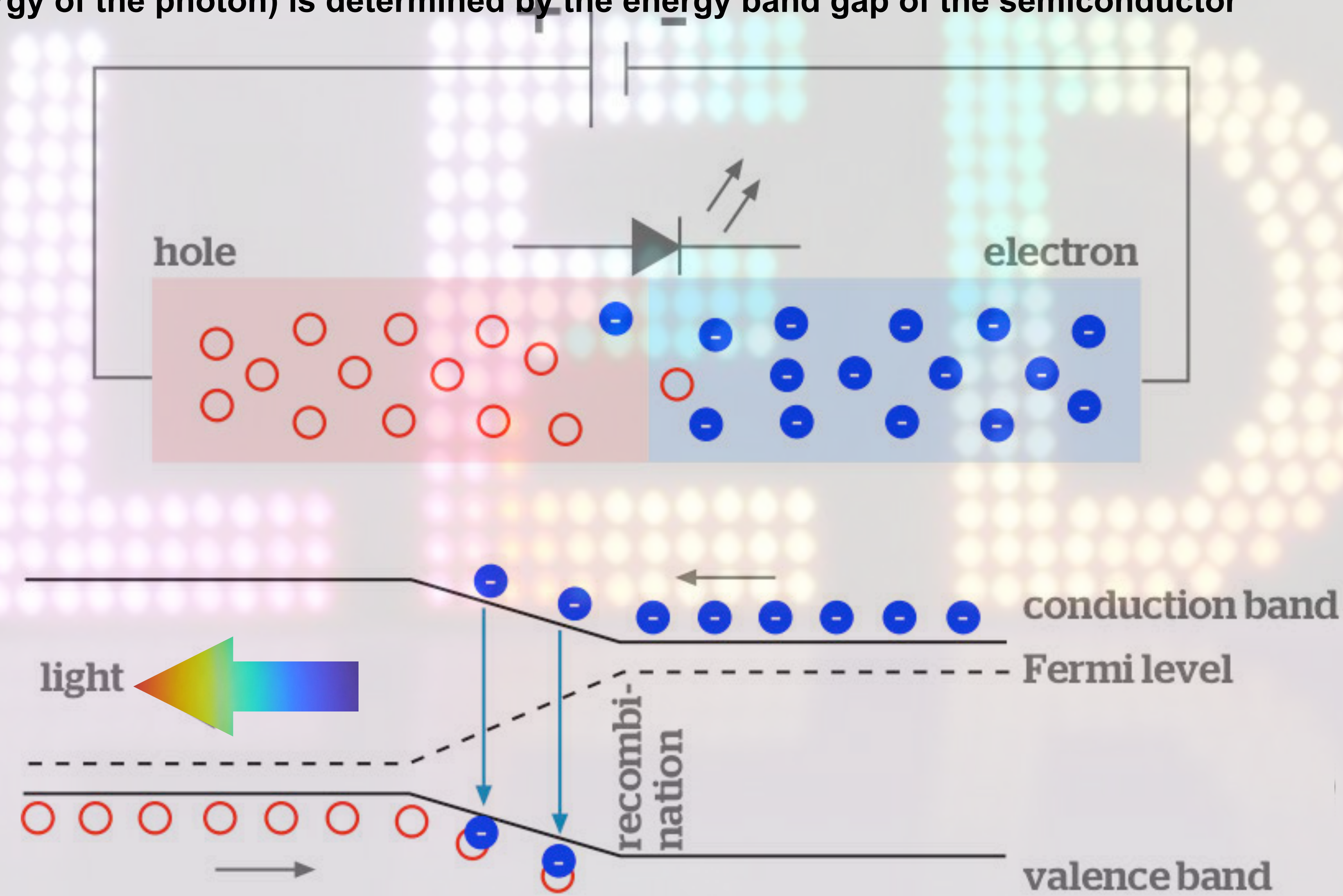
Dans la nature rien ne se crée, rien ne se perd, tout change

US Energy-Consumption in 2011

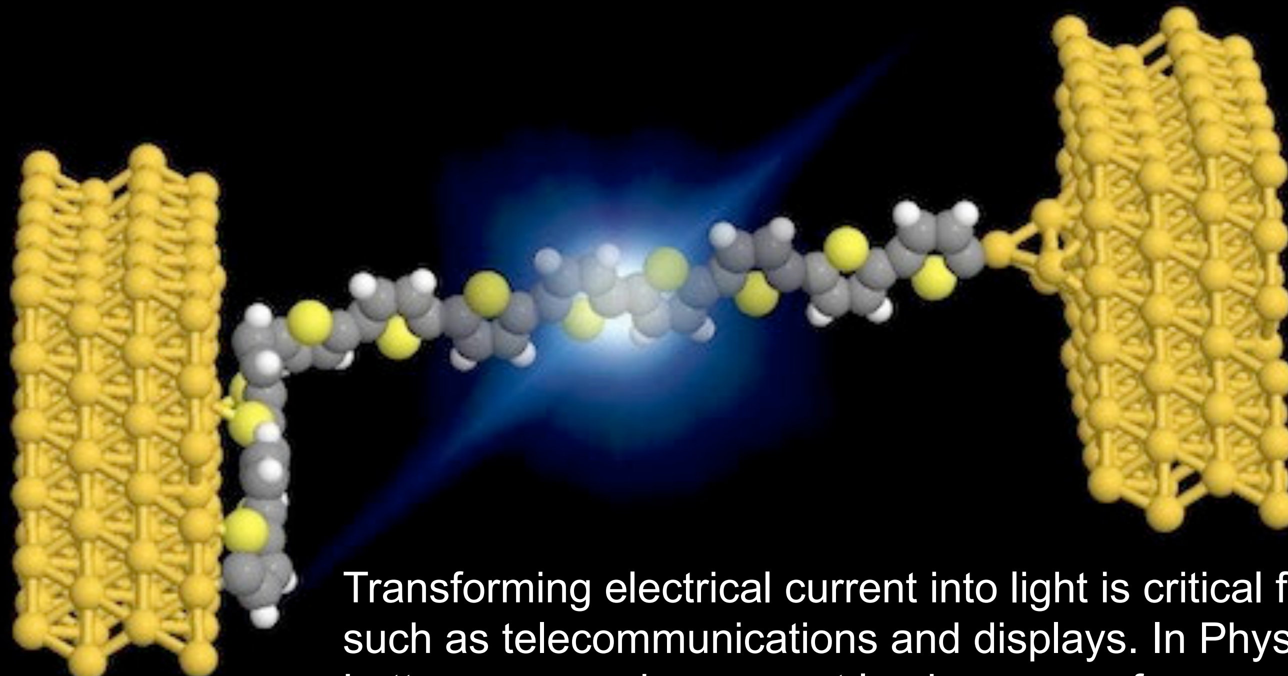



LED

It is a p–n junction diode that emits light when activated: electroluminescence, When a suitable voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. **The color of the light (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor**



Single Molecule LED



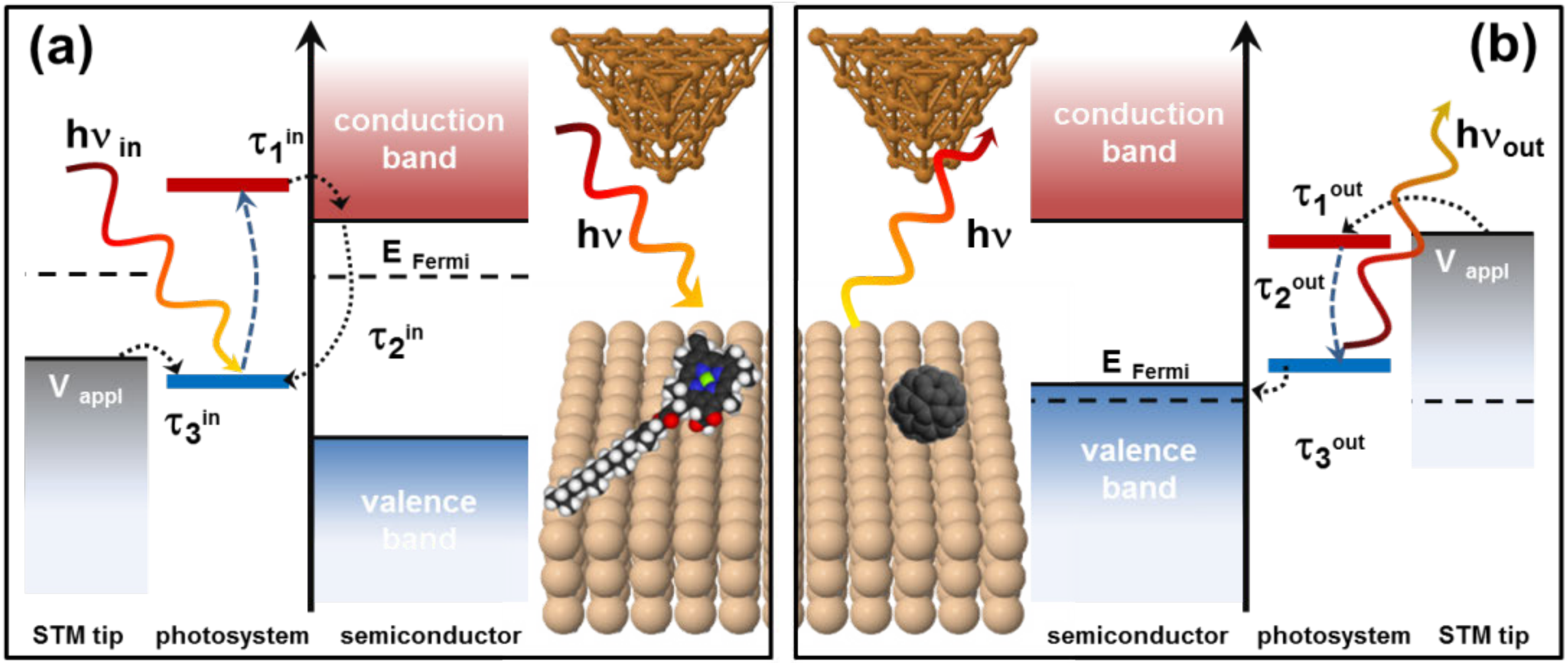
Transforming electrical current into light is critical for technologies such as telecommunications and displays. In Physical Review Letters, researchers report luminescence from a single polymer molecule, representing the smallest possible organic light-emitting diode (OLED) device.

G. Reecht et al., Phys. Rev. Lett. 112, 047403 (2014)

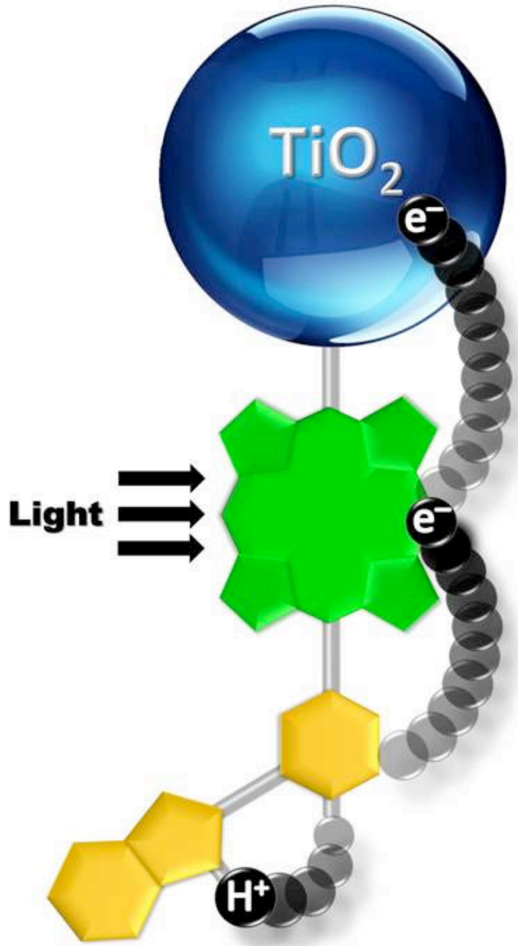
Single Molecule Photonics

light harvesting

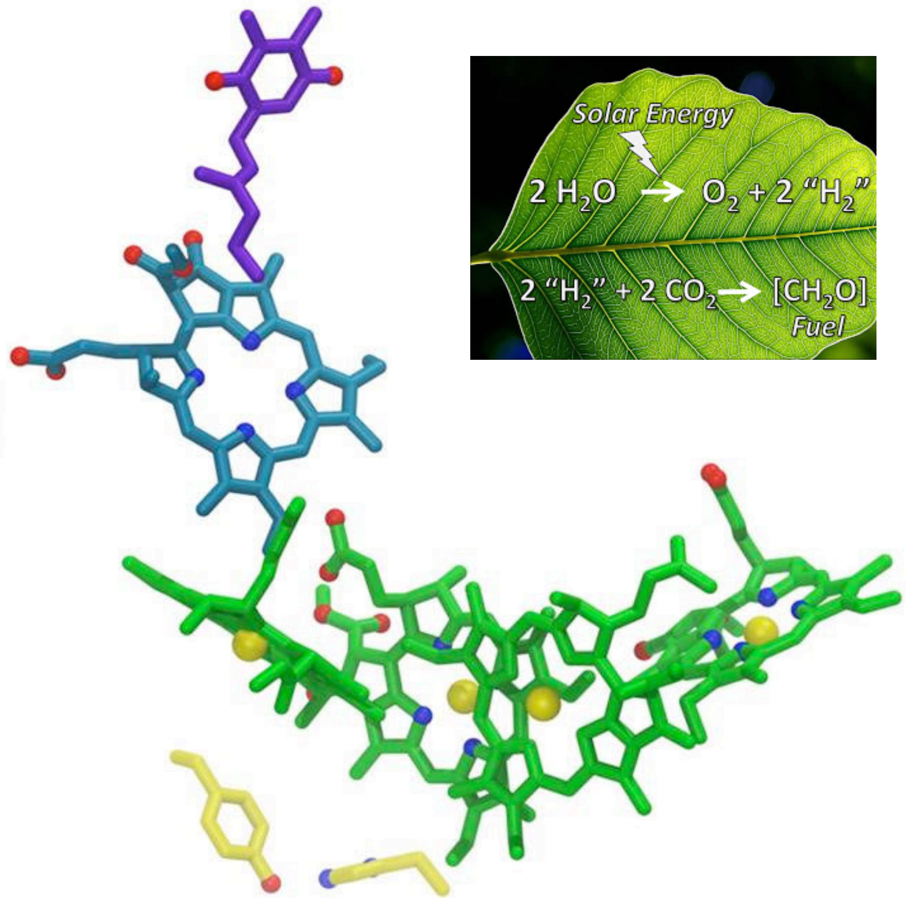
light emission



Energy Conversion

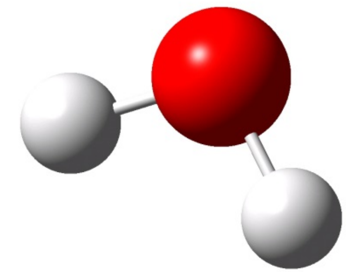


Artificial Photosystem II



Natural Photosystem II

Water H_2O

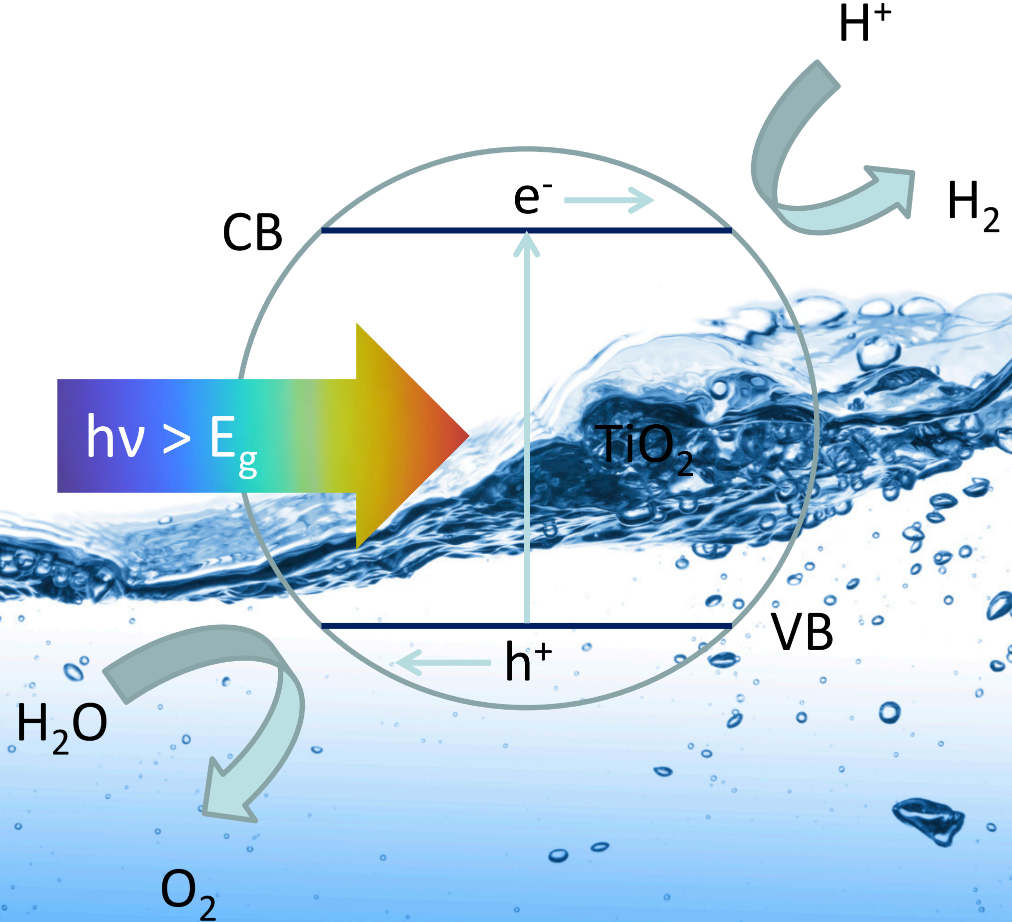


Energy Density

4450 Wh/l

Photocatalytic Water Splitting

$H_2O + 2e^- + 2h^+ \rightarrow O_2 + H_2$

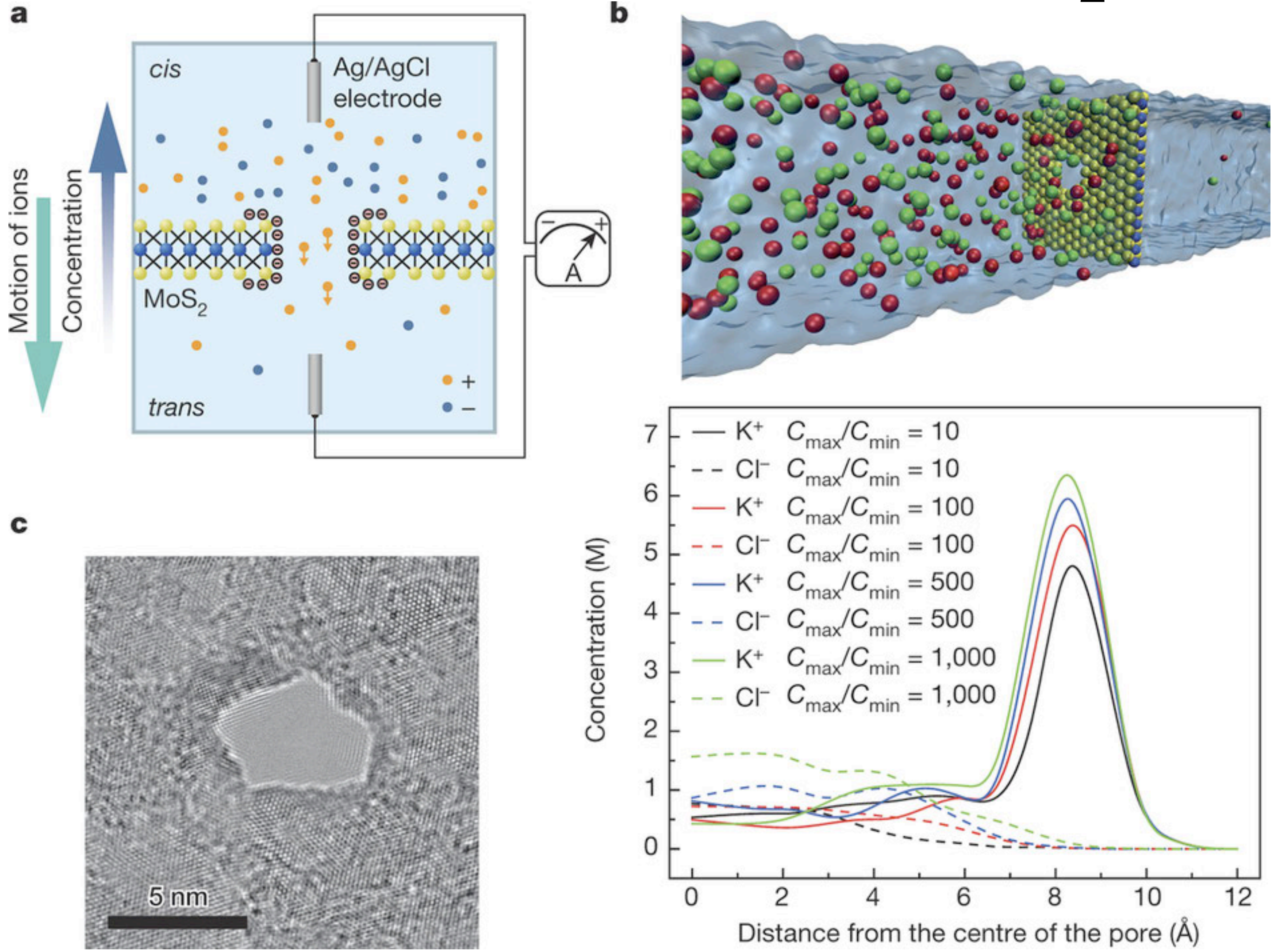


Energy Density

4450 Wh/l

Fujishima, A. and K. Honda, Nature 238 (5358): 37-38 (1972).

Harvesting Osmotic Energy with MoS_2 Nanopores



An electrolyte is driven through narrow pores either by a pressure gradient or by an osmotic potential resulting from a salt concentration gradient. Membranes made of two-dimensional materials are expected to be the most efficient, because water transport through a membrane scales inversely with membrane thickness. Estimated power density of up to 106 watts per square metre!

J. Feng et al., Nature (2016) doi:10.1038/nature18593

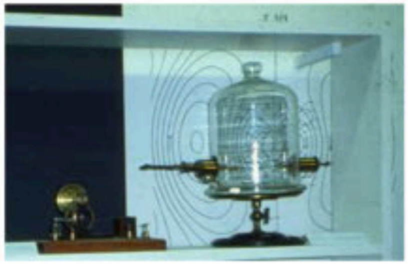
Lotus Effect

BIOINSPIRED MATERIALS

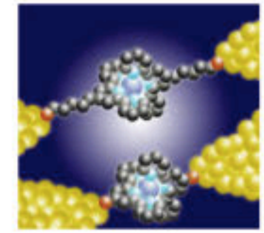
Self-cleaning Lotus effect

Lotus Effect

Basic Research





Applied Research



Product Development



Insight
must precede
application
Max Planck