The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2234-7

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

27 April - 3 May, 2011

Introduction to nanophysics

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University of Oslo
Oslo
Norway

Thank you for the invitation!

Introduction to Nanophysics

Yuri Galperin

University of Oslo, Norway

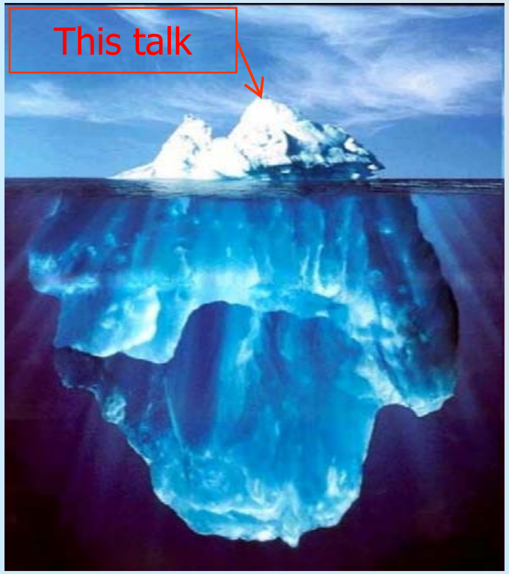
A very brief introduction to the subject

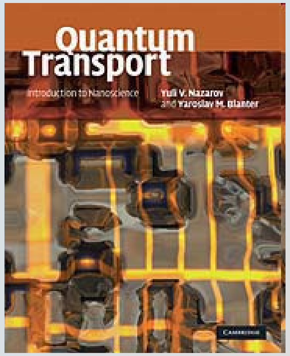
Introductory course in Oslo:
http://folk.uio.no/yurig/Nanotechnology/MEF5010.html

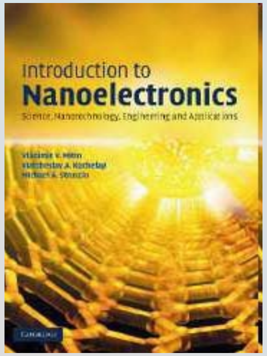
What is nanoscience and nanotechnology?

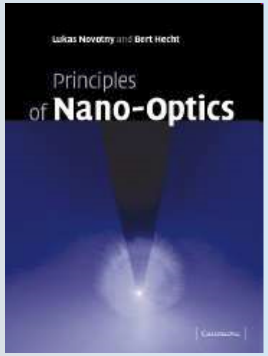
Broad definition - Nanoscience and nanotechnology are all about relating and exploiting phenomena for materials having one, two or three dimensions reduced to the nanoscale.

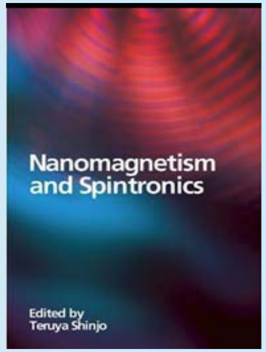
Very broad area of science and technology having many branches.

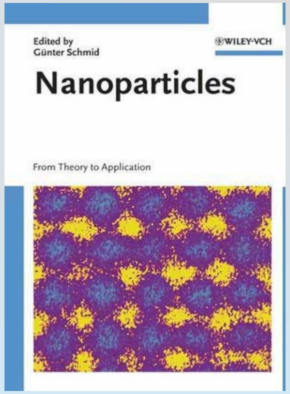


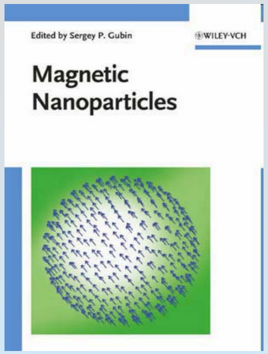


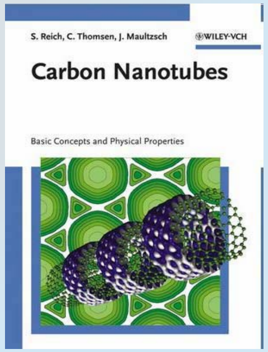


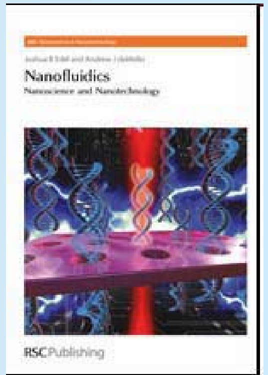












What is Nano?

Nano means Small

$1\ nm = 10^{-9}\ m = 10^{-7}\ cm$

Nano means Big !?

Nanoscale objects do not fully belong to the microcosm

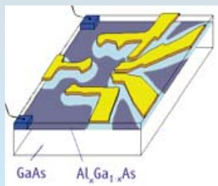
Many atoms, electrons, etc., are involved

↓

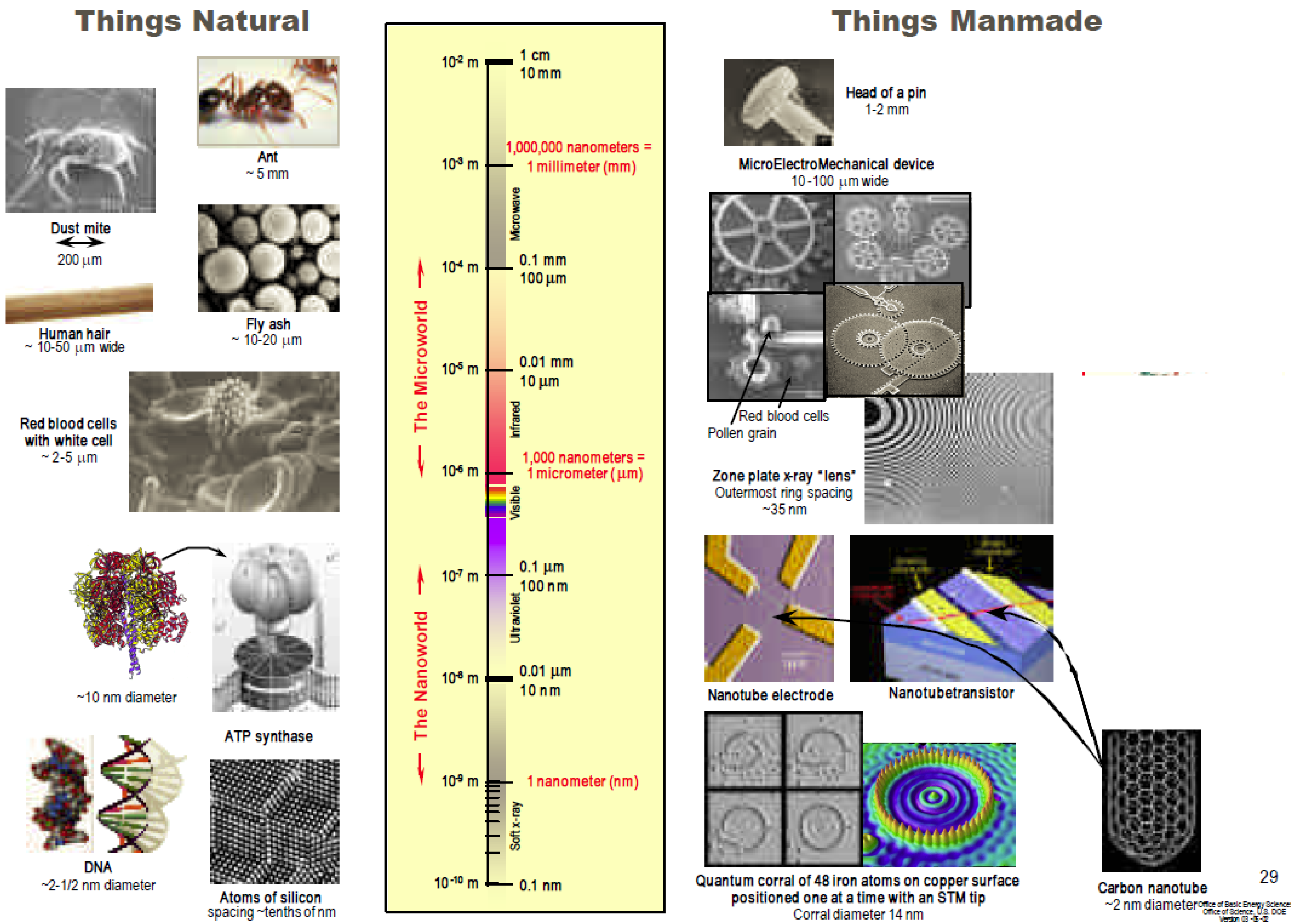
Number of degrees of freedom is large

Size →

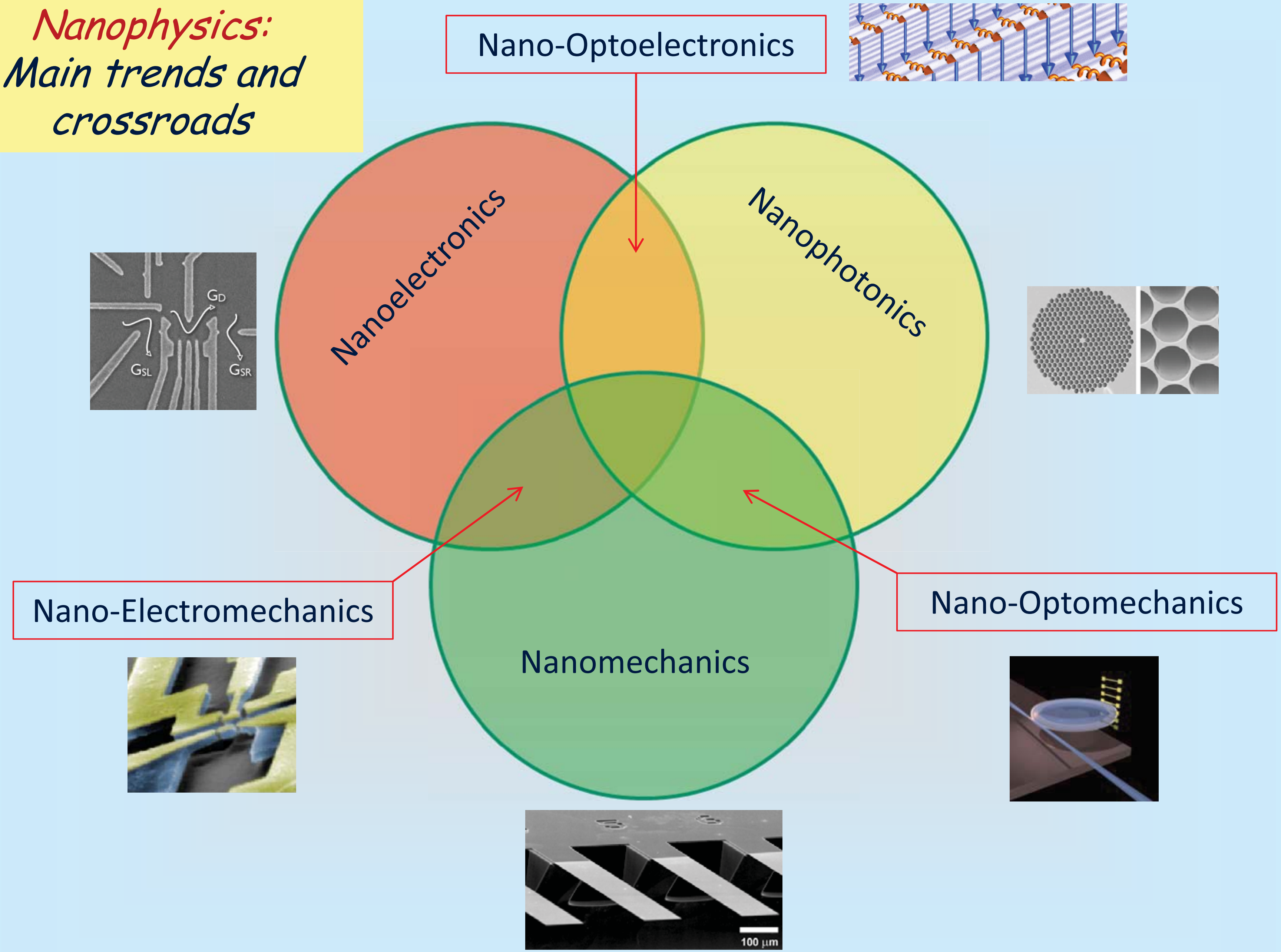
Micro	Meso	Macro
Nuclei	Nano-objects	Fluids
Atoms		Crystals
Small molecules		Glasses



The Scale of Things -- Nanometers and More



Nanophysics: Main trends and crossroads



Nanoscience is referred to as a research area devoted to studies of various phenomena in *small-size devices*.

It is a cross-disciplinary field including physics, chemistry, and to some extent biology.

The heart of nanoscience is *mesoscopic physics*.

The word ``meso'' reflects the fact that the size of the systems under consideration is located between *microscopic* (atoms) and *macroscopic* scales.

The heart of nanoscience is *mesoscopic physics*.

$$1 \text{ nm} = 10^{-9} \text{ m}$$

Characteristic scales in nanoscience

Nanometer scale

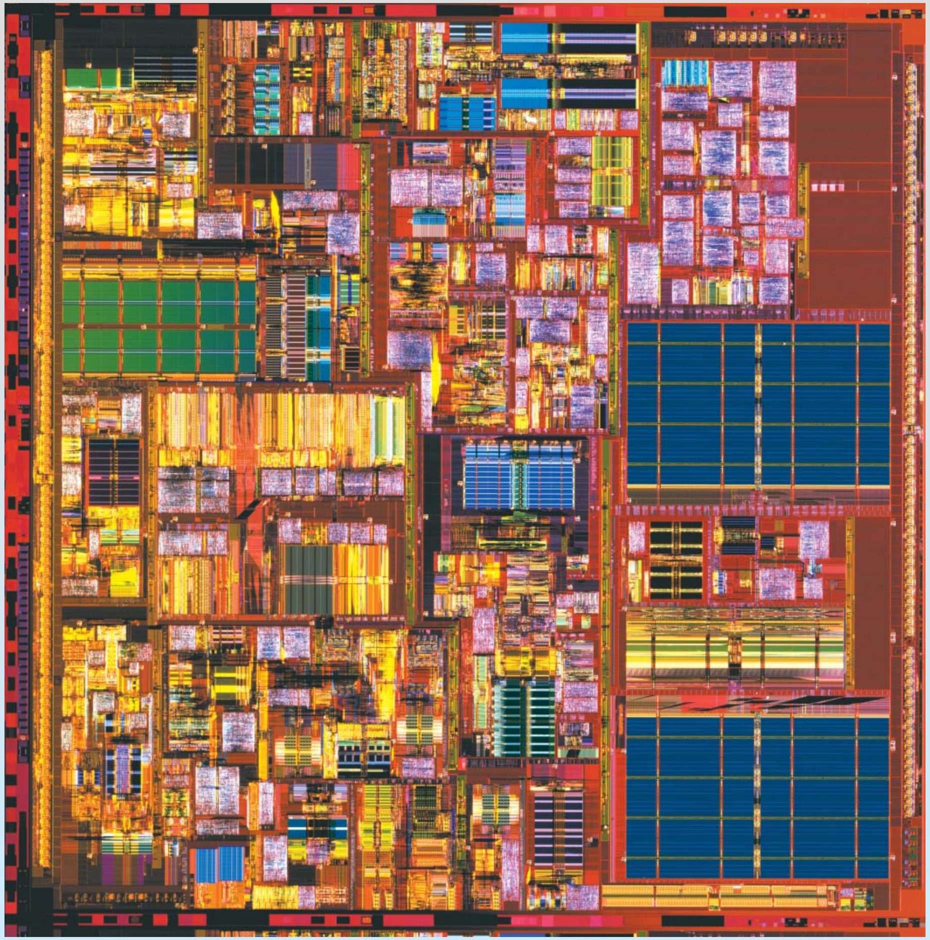
Length scale →

Atoms | **Molecules & Clusters** | **Electron mean free path** | **Bulk materials**

Micro | Meso | Macro

Modern electronic devices belong to mesoscopic scale

CMOS TECHNOLOGY



Intel's Norwood (Pentium 4 - 130 nm) processor

Intel's Prescott processor

(released March 2004):

- 150 million transistors
- 90 nm design rules
- 3.4 GHz clock frequency

DRAM chips:

4 Gb chips demonstrated

($\sim 10^9$ transistors/cm^2)

Now chips based on the design rules of 22 nm are on the way.

In 2004 we were already inside nanotechnology!

Main ingredients of nanoelectronics

- Two-dimensional electron gas (2DEG)
- Quantum wires and point contacts
- Quantum dots

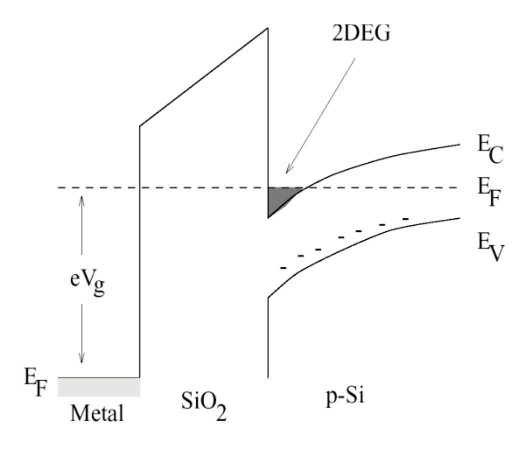
Novel materials & devices

- Nano-electro-mechanical systems
- Carbon and non-carbon nanotubes and other molecular devices
- Graphene
- Devices using superconductivity and magnetism at nanoscale
  - Devices for quantum computation
- Spintronics – manipulation electron spin

Examples

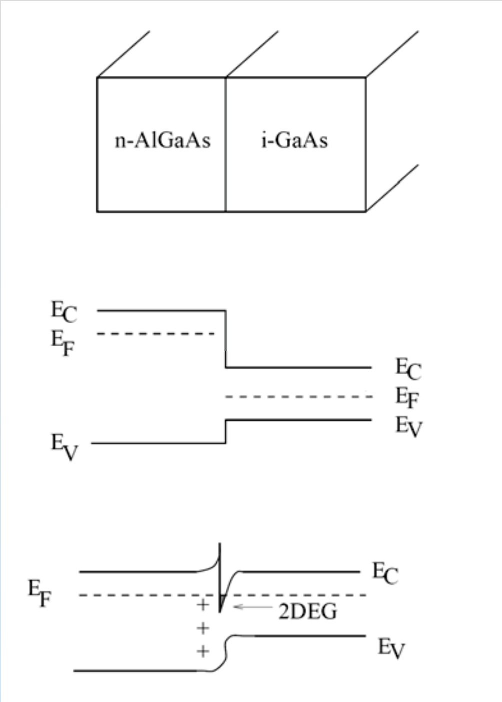
Two-dimensional Electron Gas (2DEG)

<u>Band gap engineering</u>



Metal-Oxide-Semiconductor (MOS) structures

2DEG is formed at the semiconductor-insulator interface



Semiconductor heterostructure

2DEG is formed at the interface between two semiconductors

2DEG is a generic object for new physics

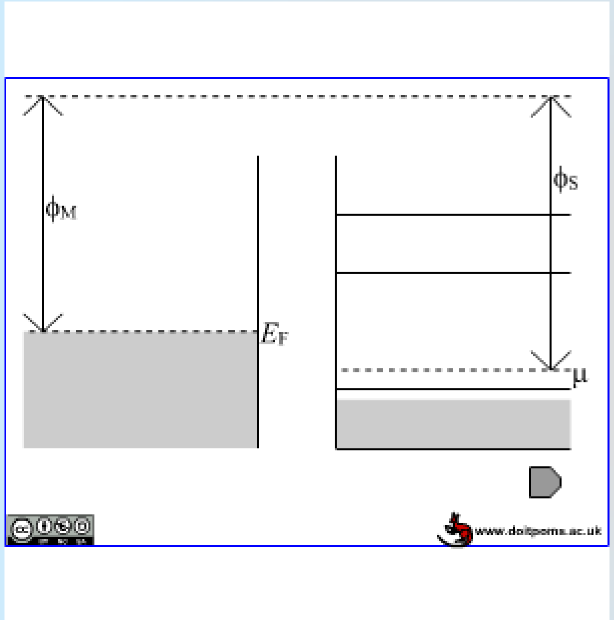
Nobel Prizes 1985, 1998, 2000

It serves as a building block for electronic devices

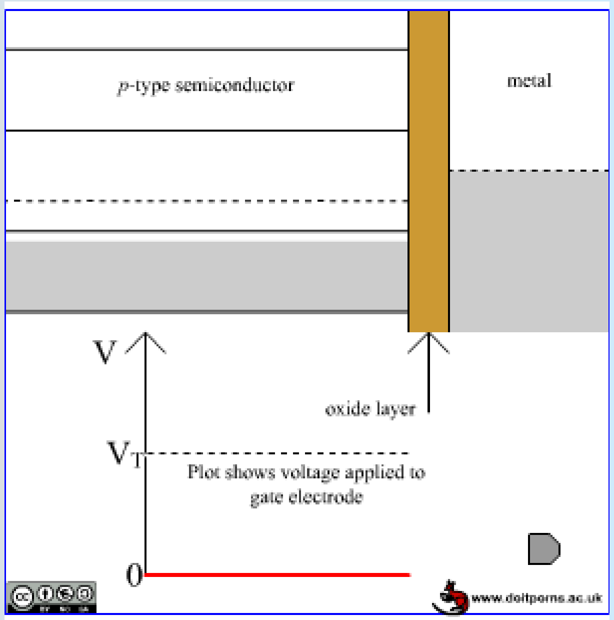
We will come back to these structures later

More about formation of 2D electron gas

Bending of the energy bands at the interface



Formation of 2D conduction channel



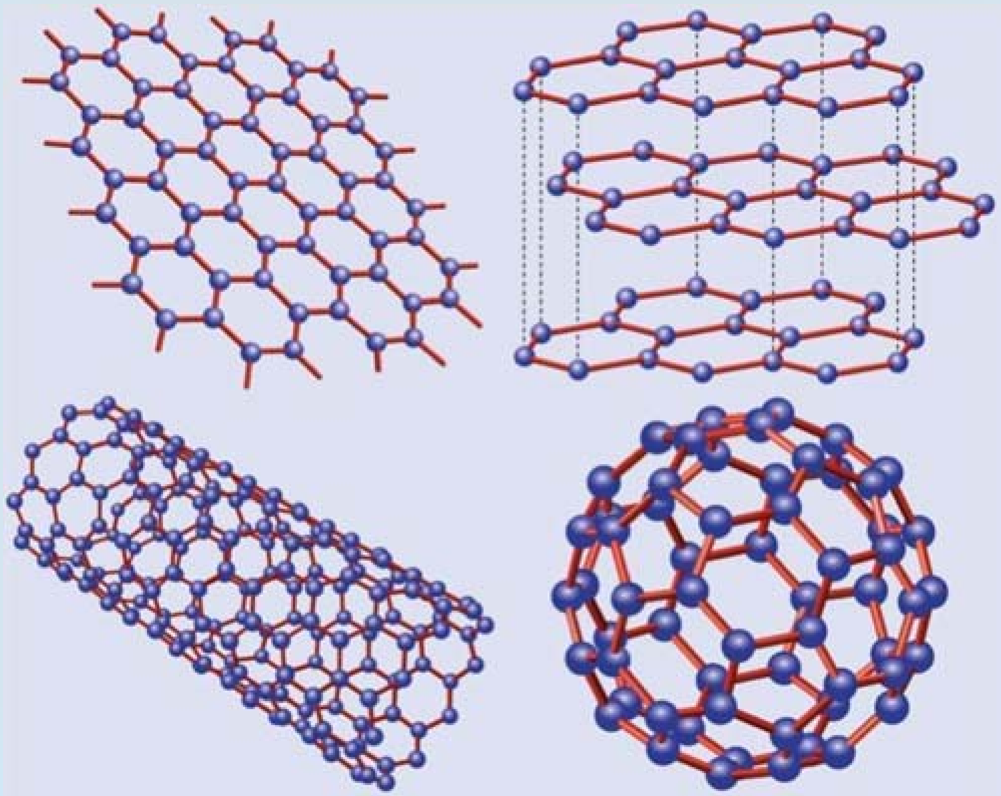
Graphene - "most two-dimensional" system imaginable

A suspended sheet of pure graphene – a plane layer of C atoms bonded together in a honeycomb lattice – is the "most two-dimensional" system imaginable.

A.J. Leggett

Graphene is a honeycomb lattice of carbon atoms.

Graphite can be viewed as a stack of graphene layers.

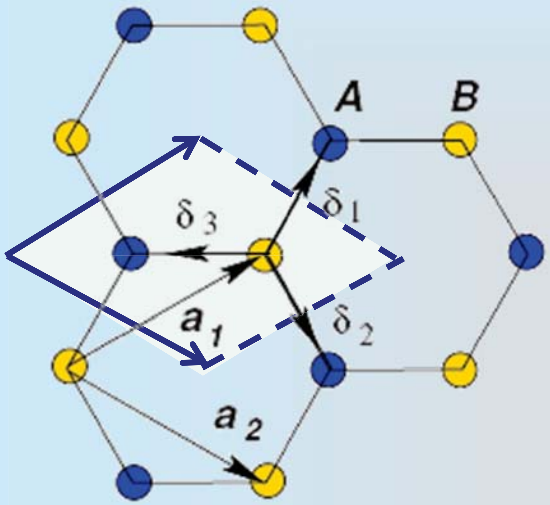


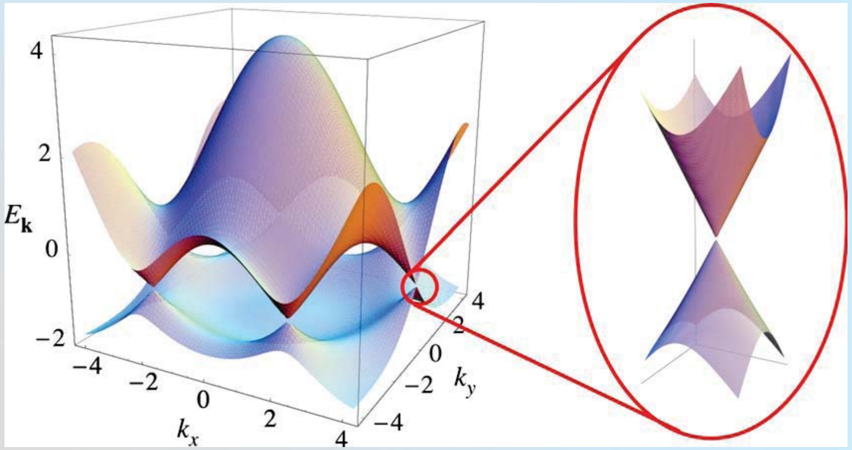
Carbon nanotubes are rolled-up cylinders of graphene

Fullerenes C_{60} are molecules consisting of wrapped graphene by the introduction of pentagons on the hexagonal lattice.

Symmetry matters!

> Happy families are all alike; every unhappy family is unhappy in its own way.
>
> **Leo Tolstoy**, *Anna Karenina*





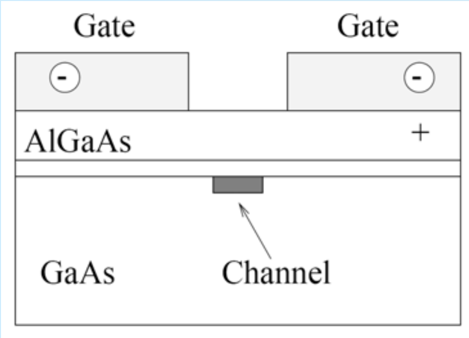
Like relativistic particles !

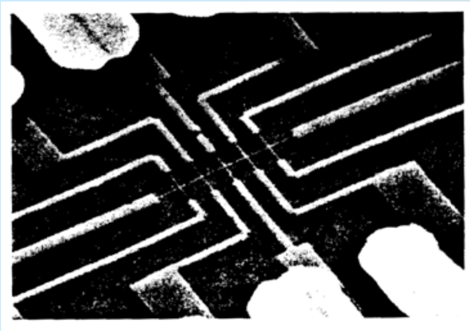
The Nobel Prize in Physics
2010

Andre
Geim

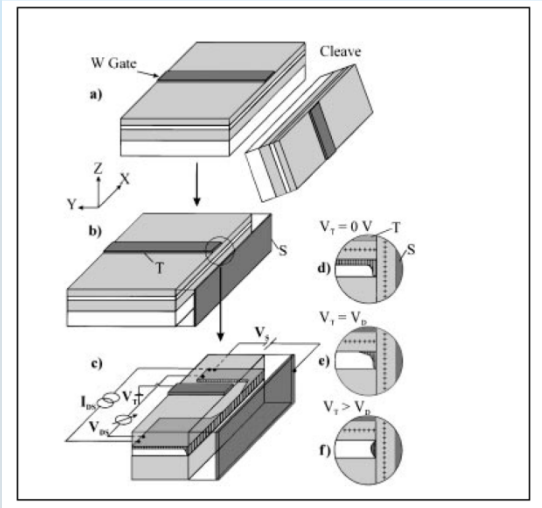
Konstantin
Novoselov

Quantum Wires and Point Contacts

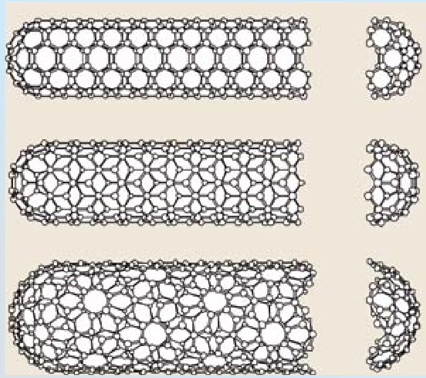


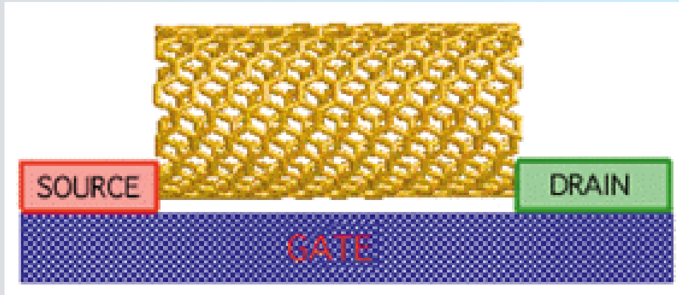


Split-gate structures

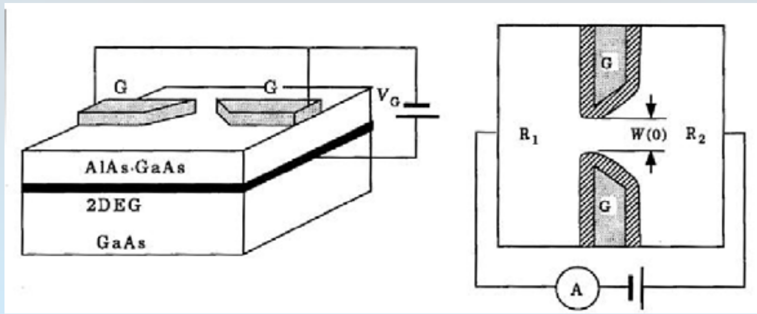


Cleaved structures

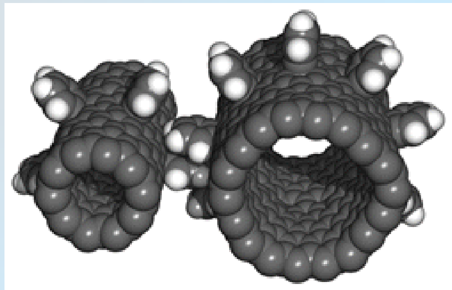




"Back-end" parts of nanodevices

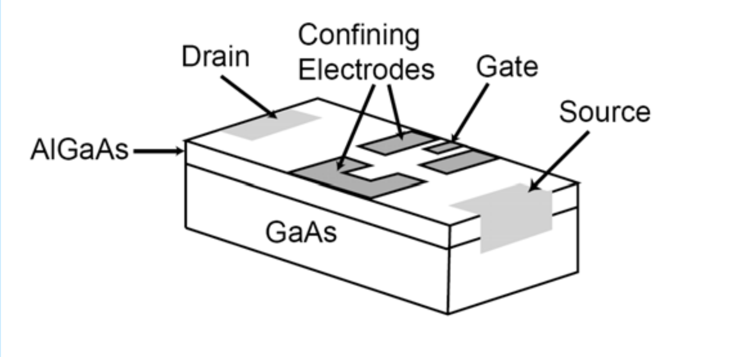


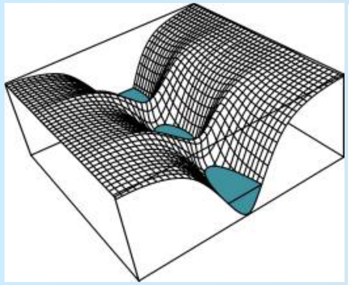
Point contacts

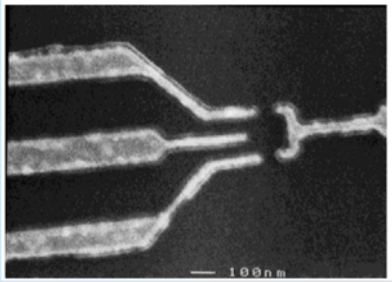


Carbon nanotubes

Quantum Dots

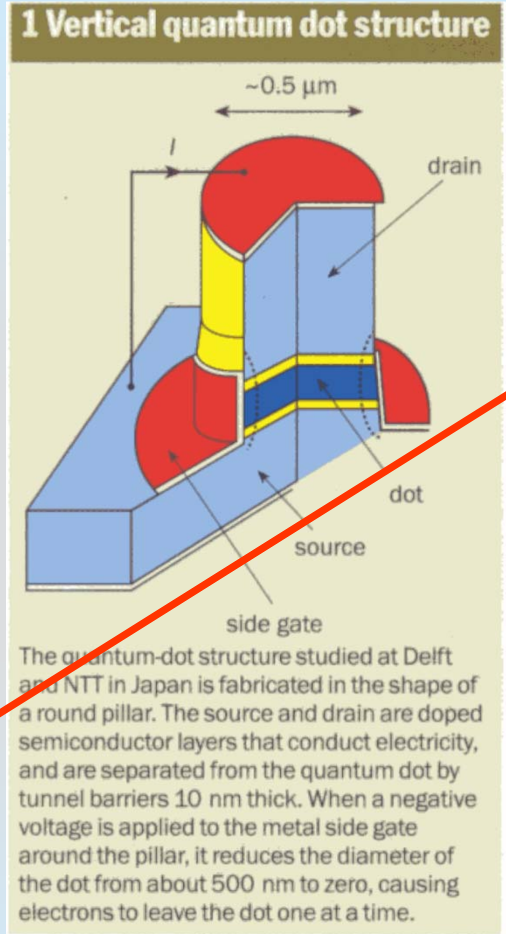




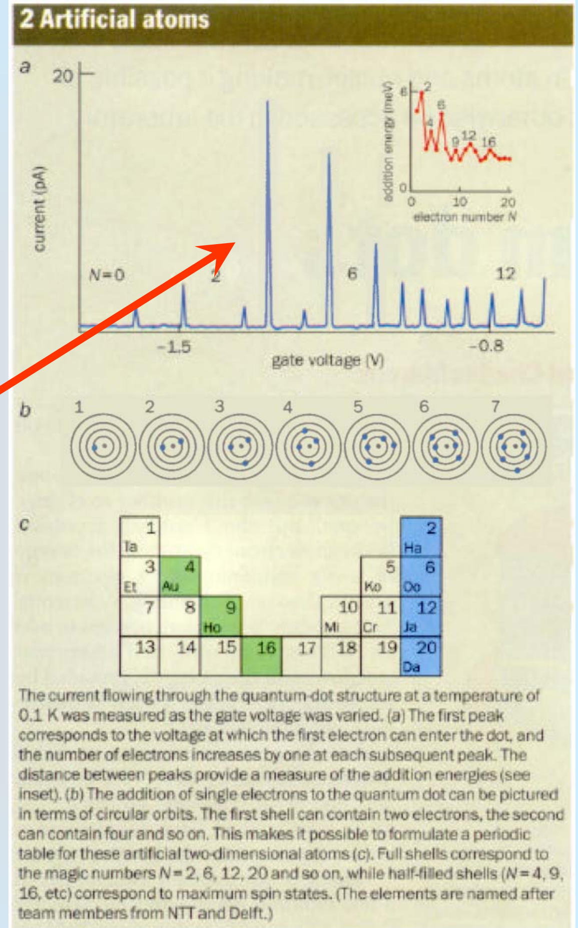


Lateral quantum dots

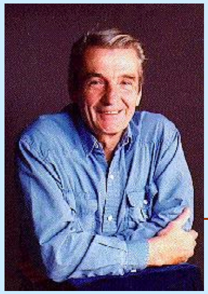
Coulomb blockage!



Vertical



Artificial atoms – new periodic table

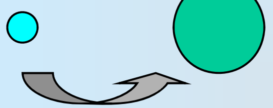


Ivar Giæver

Coulomb blockade

Gate

Electron



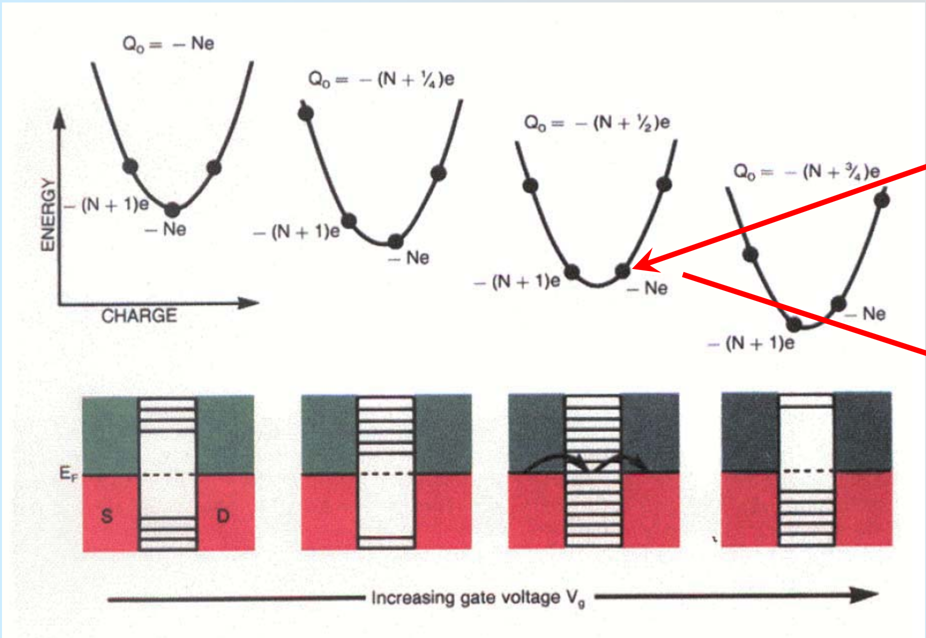
Dot

Cost $E = QV_g + \frac{Q^2}{2C}$

Repulsion at the dot

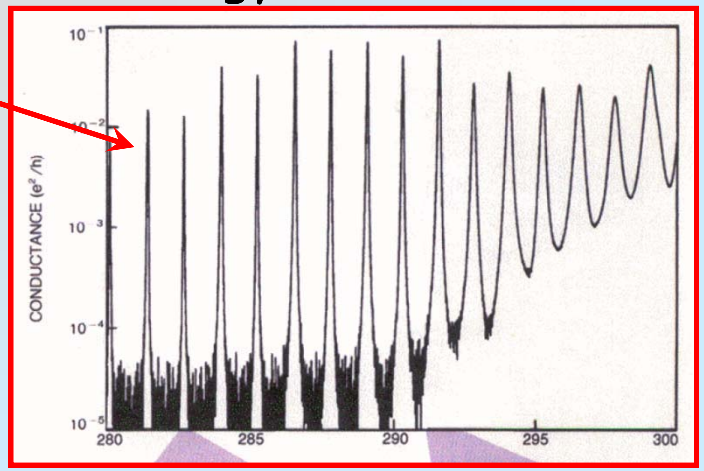
Attraction to the gate

$Q = -Ne$

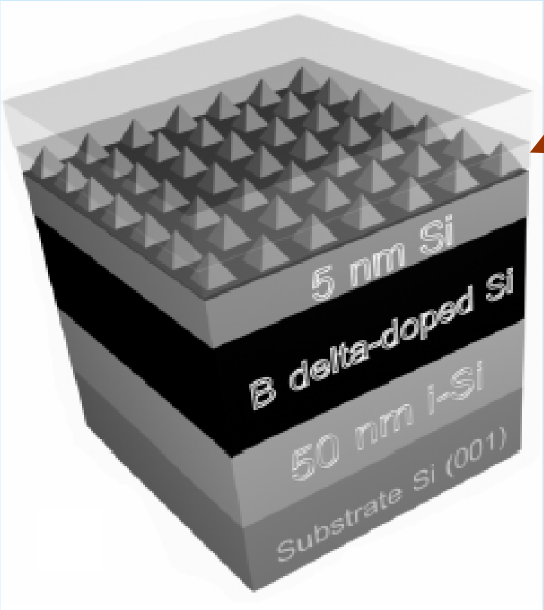


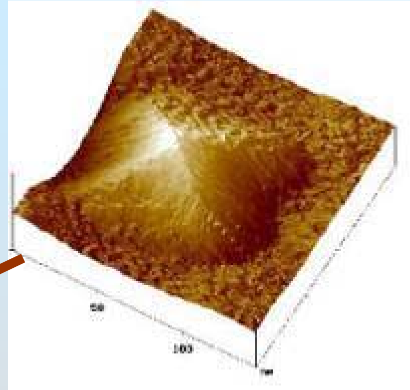
At $V_g = -\left(N + \frac{1}{2}\right)\frac{e}{C}$

the energy cost vanishes !



Single-electron transistor (SET)



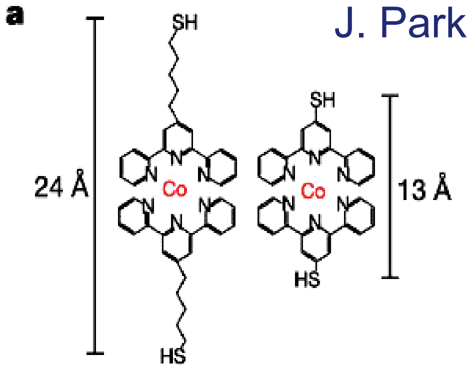


Self-assembled quantum dots are periodic arrays of “artificial atoms”.

They are considered to be promising systems for heterostructure lasers.

Our project: Ge-in-Si arrays

SINGLE-ELECTRON
SINGLE-MOLECULE TRANSISTORS

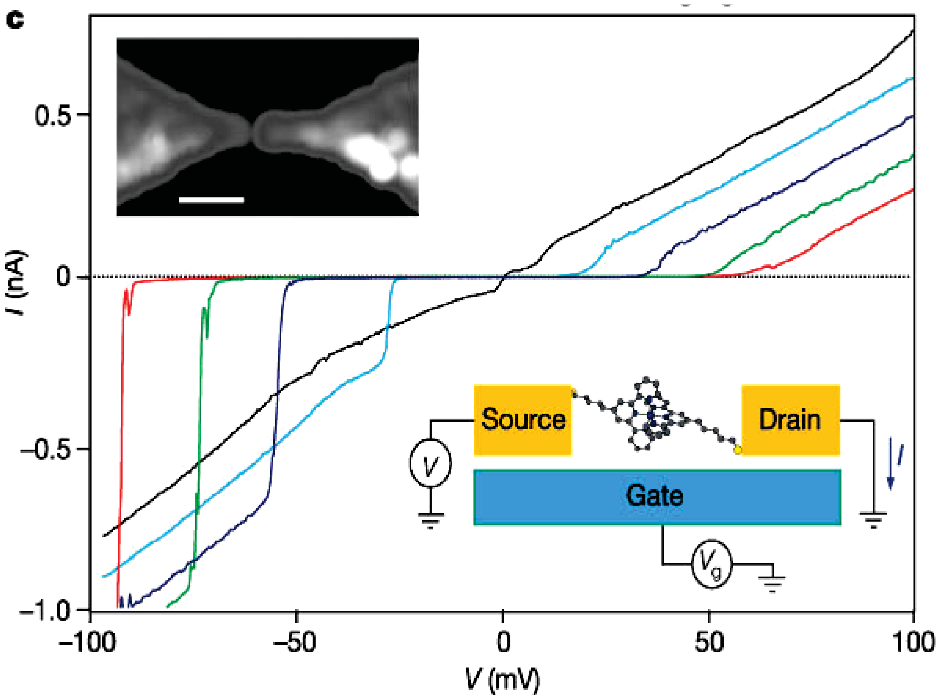


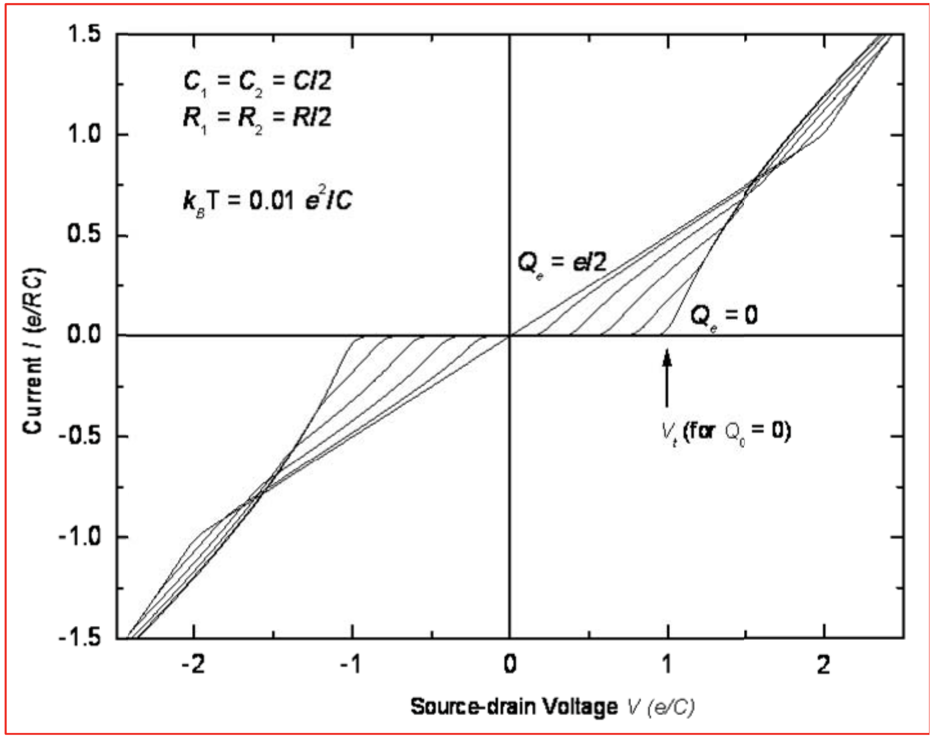
J. Park *et al.* (2002)

see also:
- E. S. Soldatov *et al.* (1996)
- H. Park *et al.* (2000)
- N. Zhitenev *et al.* (2002)
- S. Kubatkin *et al.* (2003)

Molecular electronics

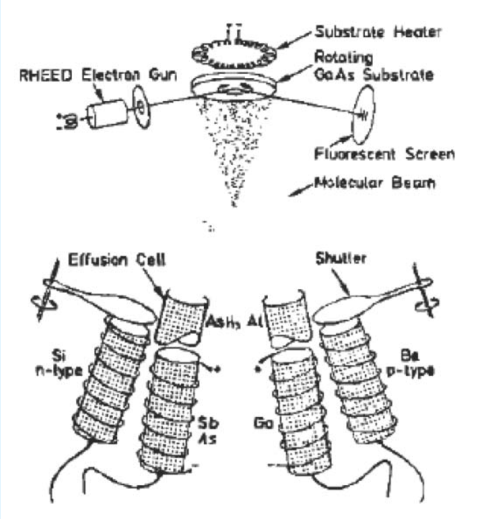
SET within the "Orthodox" theory:



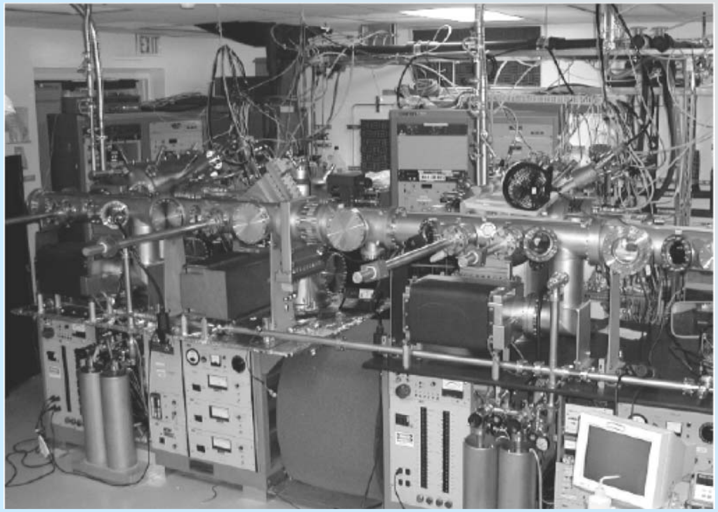


Instrumentation for nanoscience and nanotechnology

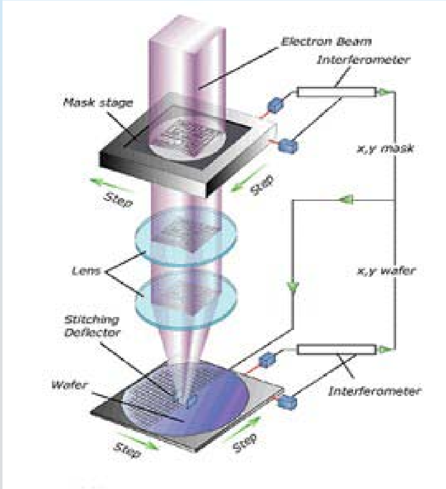
Growth

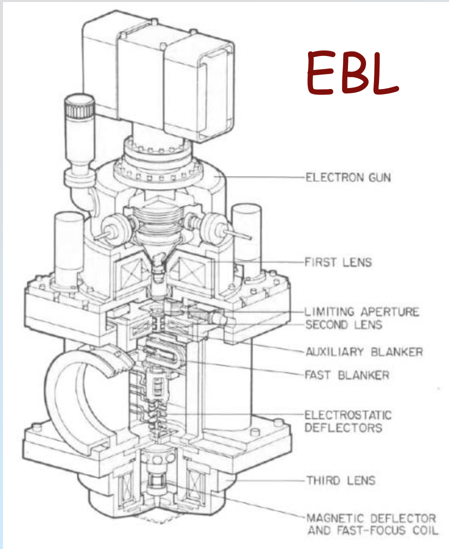


MBE



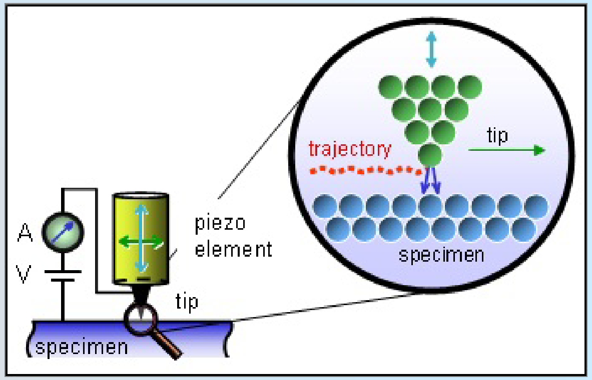
Fabrication



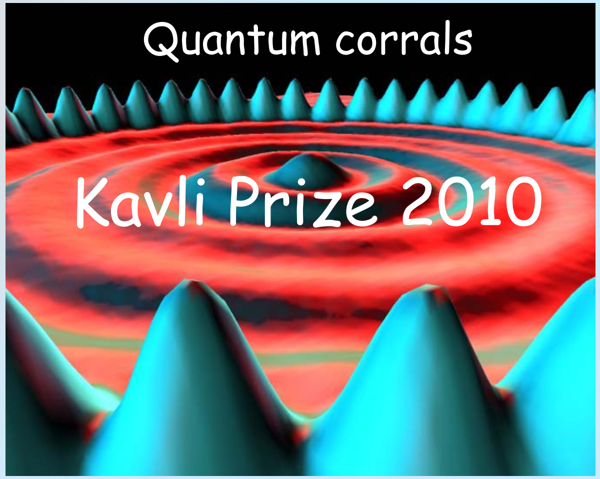


EBL

Characterization



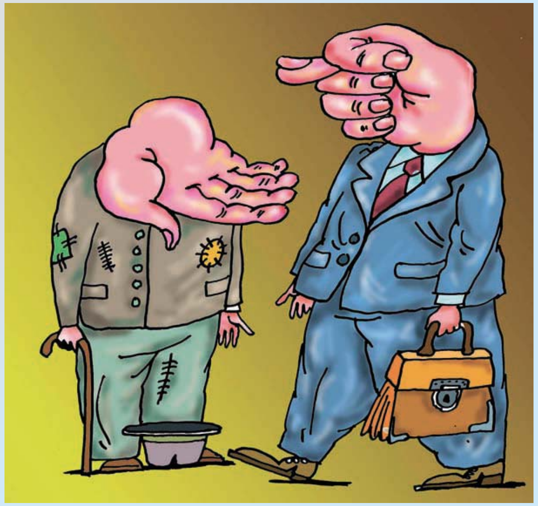
STM



Even a modest nanocenter needs:

- Start-up for instrumentation for > 20 mil. US $ (in addition to a proper building)
- Proper running costs (rather high)
- Research personnel highly qualified both in experiment and theory

The center will not be efficient without all these ingredients.

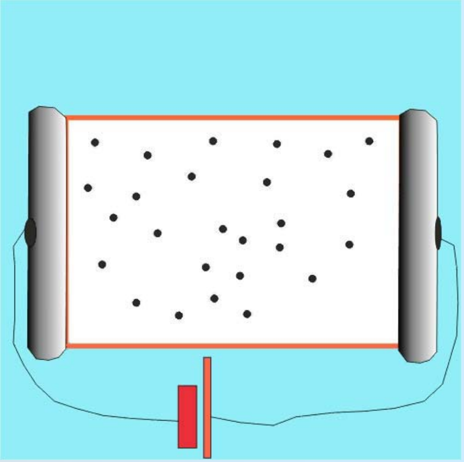


Scientist – bureaucrat scheme

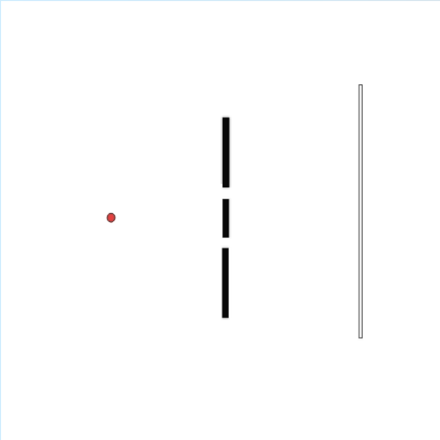
New laws of Nature at nanoscale?

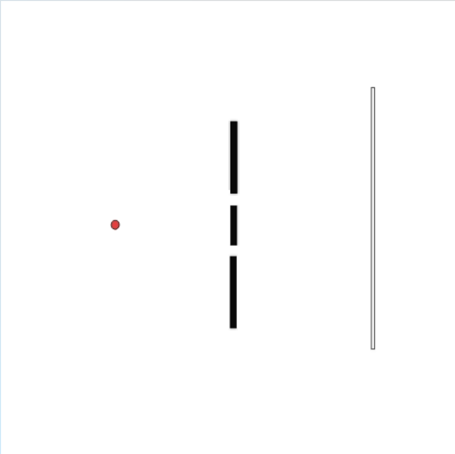
In a classical resistor, the resistance is due to electron scattering.

Otherwise electrons are just accelerated by the electric field.

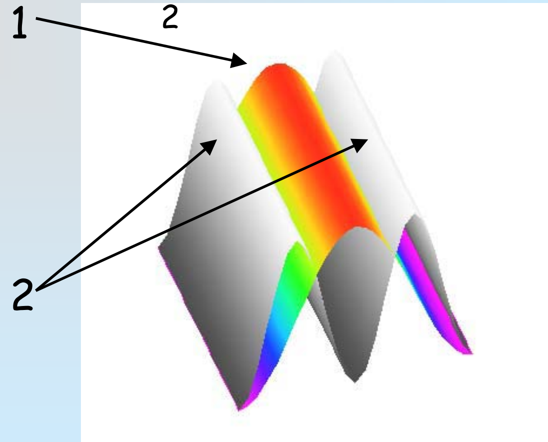


QM: Particle or wave?

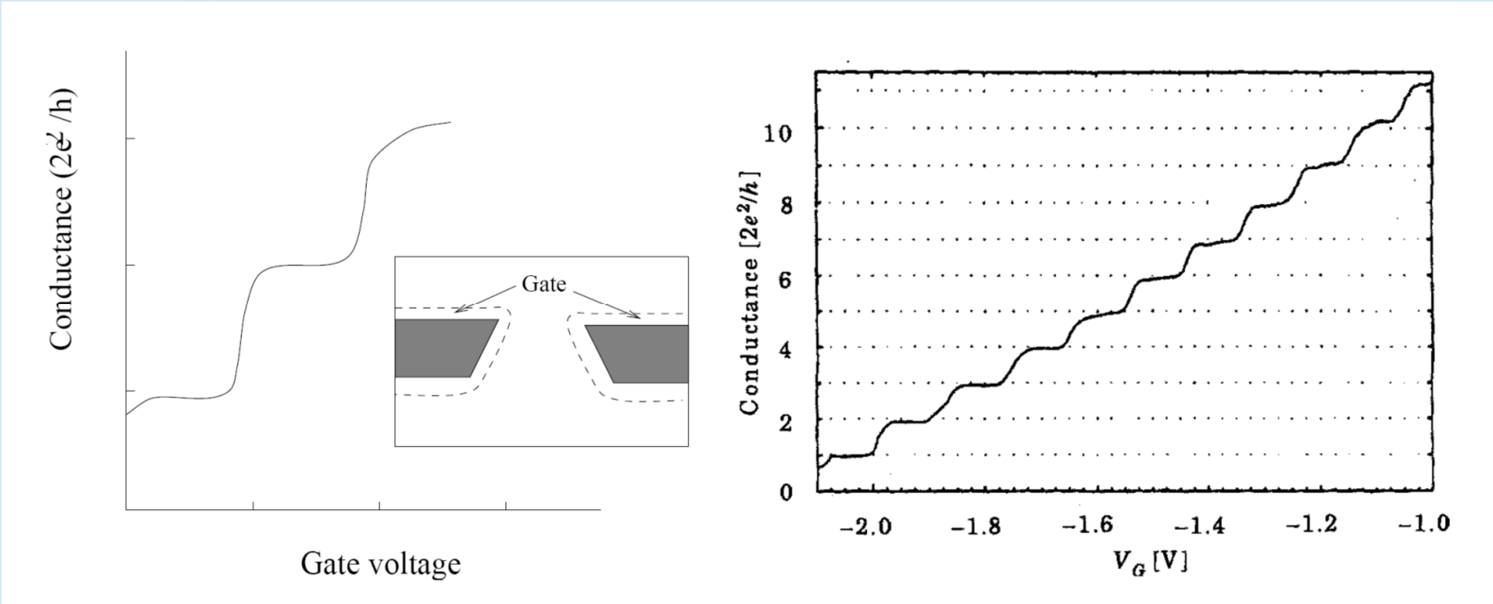




Quantum modes in the wire



Quantization of conductance vs. gate voltage!



New universal unit of resistance – ***h/e^2***

Absent in classical theory

Basic problems

- Nanoscale systems require understanding
  - Quantum transport
  - Role of electron-electron interaction, which is more pronounced in low-dimensional systems
  - Role of disorder
  - Role of contacts and electromagnetic environment
- Nano-devices are usually out of equilibrium, which requires special understanding

All these issues are far from being fully understood.

⇓

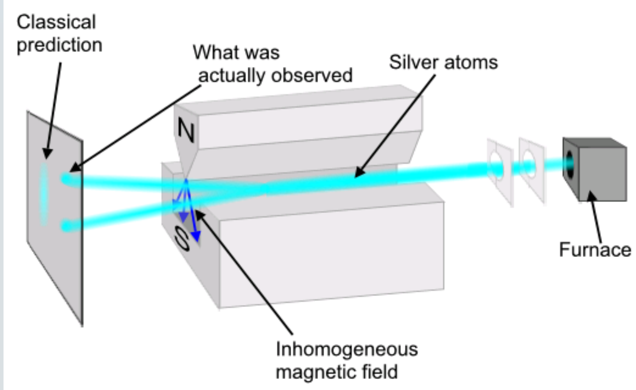
New research area with rich physics and chemistry!

Electron spin

Two types of experimental evidence which arose in the 1920s suggested an additional property of the electron.

One was the closely spaced splitting of the hydrogen spectral lines, called fine structure.

The other was the Stern-Gerlach experiment which showed in 1922 that a beam of silver atoms directed through an inhomogeneous magnetic field would be forced into two beams.

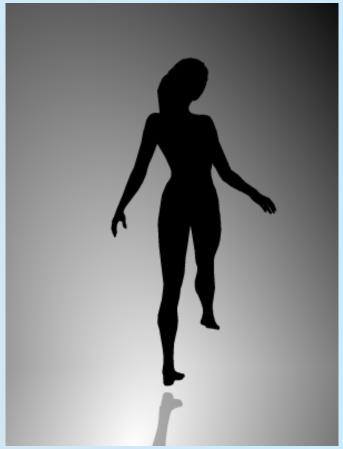


It was recognized in the early years of quantum mechanics that atomic spectra measured in an external magnetic cannot be predicted with just *orbital quantum numbers*. A solution to this problem was suggested in early 1925 by George Uhlenbeck and Samuel Goudsmit, students of Paul Ehrenfest (who rejected the idea), and independently by Ralph Kronig, one of Lame's assistants.

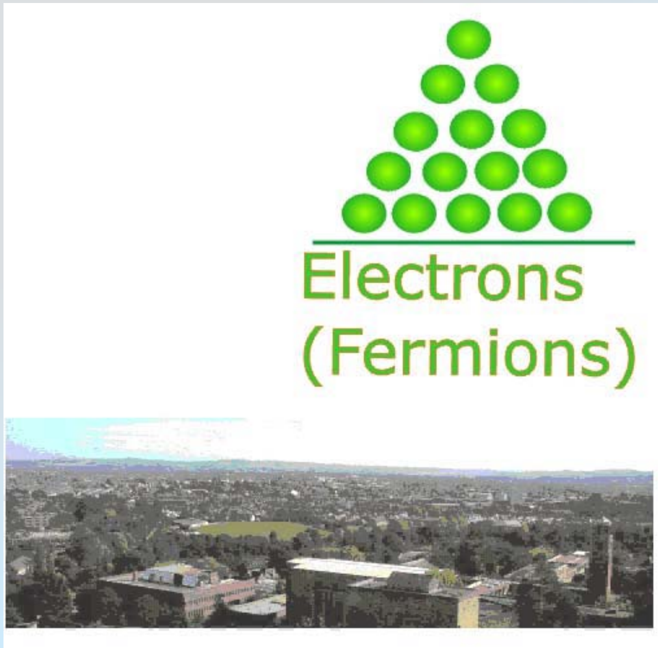
Uhlenbeck, Goudsmit, and Kronig introduced the idea of the self-rotation of the electron, which would naturally give rise to an angular momentum vector in addition to the one associated with orbital motion.

Quantum Mechanics of Identical Particles: Spin and Statistics

In quantum mechanics **spin** is a fundamental characteristic property of particles. Spin is a type of angular momentum.



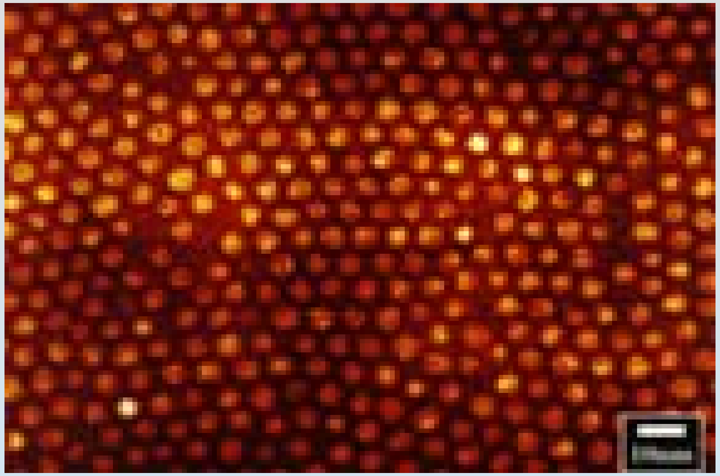
When combined with the spin-statistics theorem, the spin of electrons results in the Pauli exclusion principle, which in turn underlies the periodic table of chemical elements.



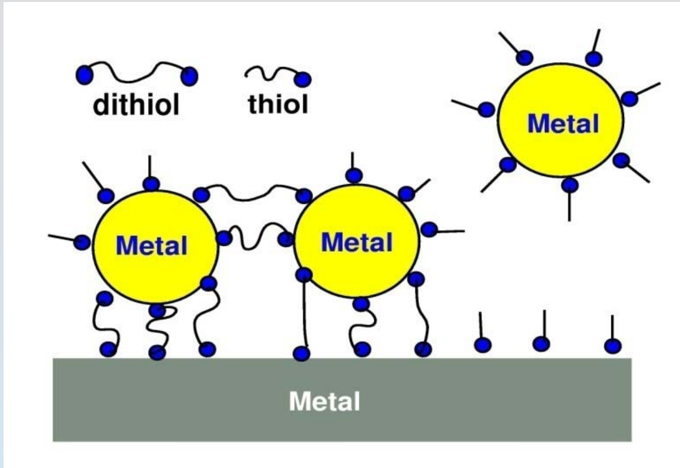
Electrons are fermions, while photons, phonons and magnons are bosons

Nano-electromechanical systems

Nanomaterials



Encapsulated 4 nm Au particles self-assembled into a 2D array supported by a thin film, Anders *et al*., 1995



Scheme for molecular manufacturing

In nanomaterials electrical and mechanical energies are comparable

↓

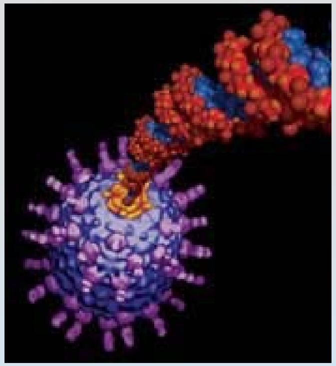
Electrical and mechanical modes are strongly coupled

↓

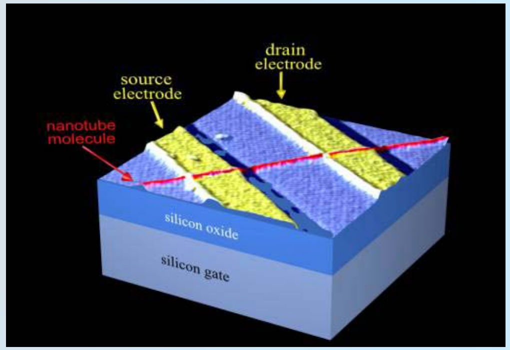
Nano-electro-mechanics

Concrete systems

Electron “shuttles”

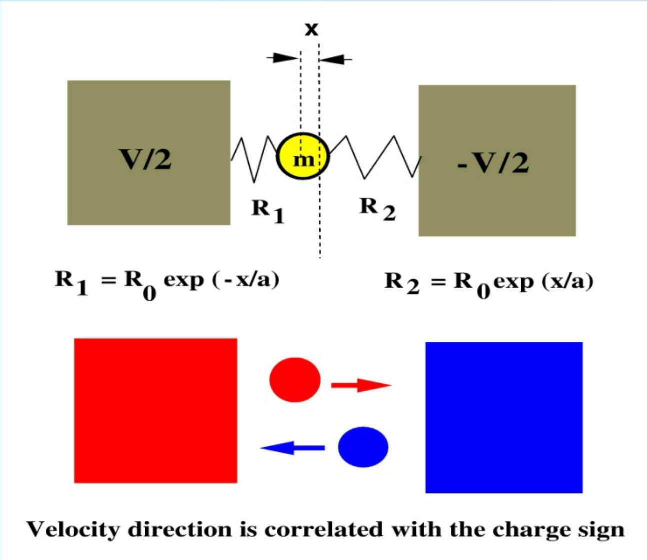


Molecular motors



Carbon nanotubes

"Shuttle" transfer of electrons

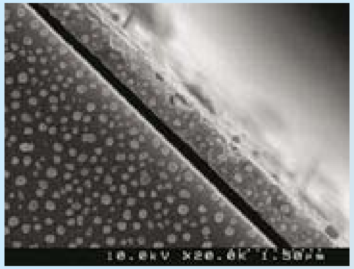


A movable cluster "conveys" electron one by one

In some cases electro-mechanic instabilities can take place

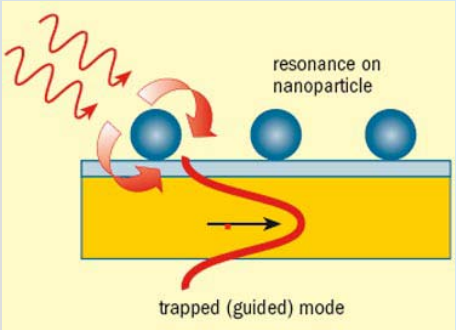
"Shuttle" transport has been observed in several concrete systems

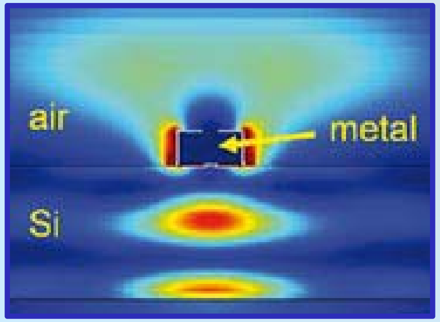
Solar cells with nanoparticles: Nanoplasmonics



Metallic nanoparticles embedded in the host system close to the active layer

Main principle: Plasmon resonances due to nanoparticles strongly enhance the time, which photons spend close to the active layer





Simulation of increased light intensity beneath a metal nanoparticle on a silicon cell

Key players: Centre for Sustainable Energy Systems at the Australian National University (ANU) ; Caltech, US; FOM-Institute, AMOLF, the Netherlands.

More about physical scales

Classical length – electron mean free path, ℓ_e

Quantum length – de Broglie wavelength of an electron having the Fermi energy:

$$\lambda_F = h/\sqrt{2m^* E_F}$$

h - Planck constant, m^* - effective mass,
E_F - Fermi energy.

This scale is relevant to the *size quantization* – quantum films, wires, and dots

Another important scale – phase coherence length, ℓ_ϕ

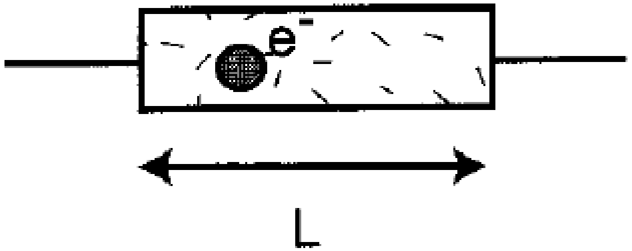
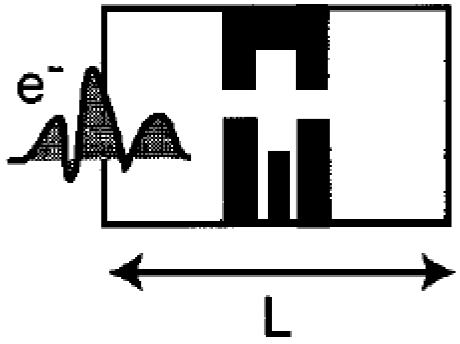
Scale introduced by Coulomb interaction and depending on the device capacitance, C

- relevant to *single-electron tunneling*

Interplay between different scales leads to a rich picture of transport through nanosystems.

The specific properties of different regimes can be used for various applications.

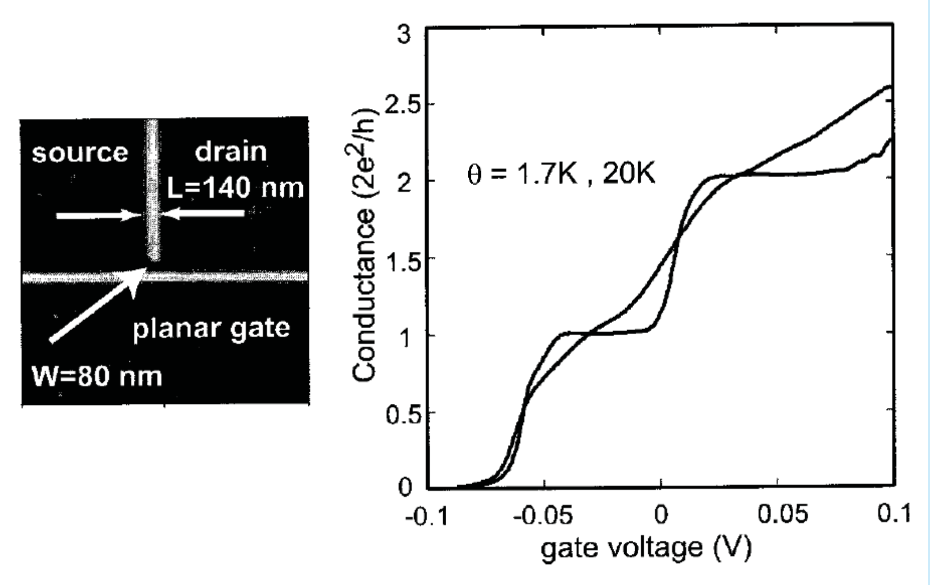
Basic classification of transport regimes

conventional device: 		mesoscopic device: 	
$L >> l_e$	diffusive	$L \lesssim l_e$	ballistic
$L >> l_\phi$	incoherent	$L \lesssim l_\phi$	phase coherent
$L >> \lambda_F$	no size quantization	$L \lesssim \lambda_F$	size quantization
$e^2/C < k_B\Theta$	no single electron charging	$e^2/C \gtrsim k_B\Theta$	single electron charging effects

Ballistic transport, $L < \ell_e$, *quantum point contact*

To the left, the surface topography of a GaAs microchip is shown. The picture has been taken with an atomic force microscope.

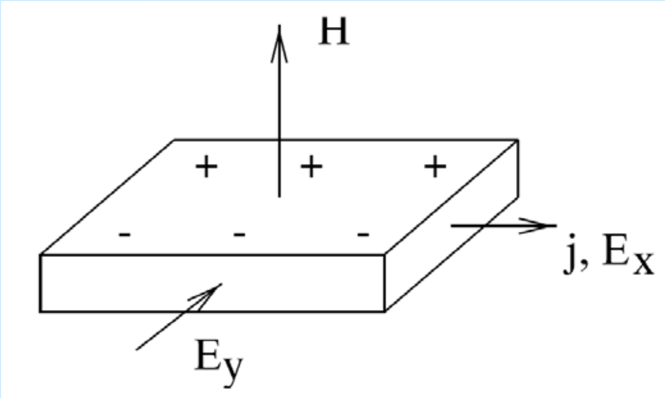
The chip hosts a quantum film about 30 nm below its surface, which is removed underneath the bright lines. A small and short wire of length 140 nm and width 80 nm connects source and drain.



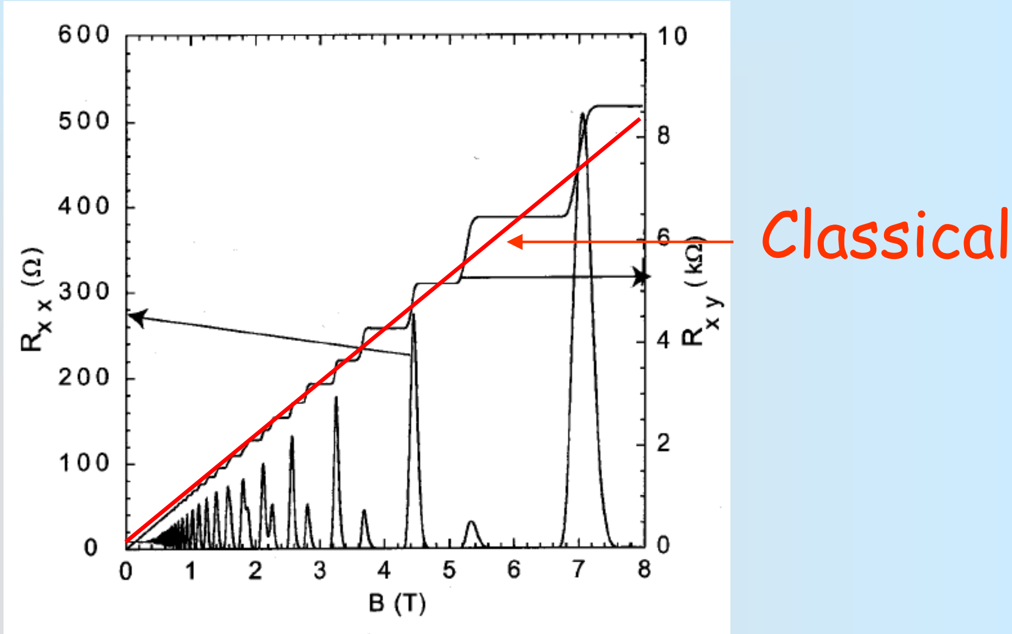
The measurement to the right shows the conductance of the wire as a function of the gate voltage.

At low temperatures, a conductance quantization in units of $2e^2/h$ is visible, which vanishes around 20 K.

The quantum Hall effects and Shubnikov-de Haas oscillations



Hall effect



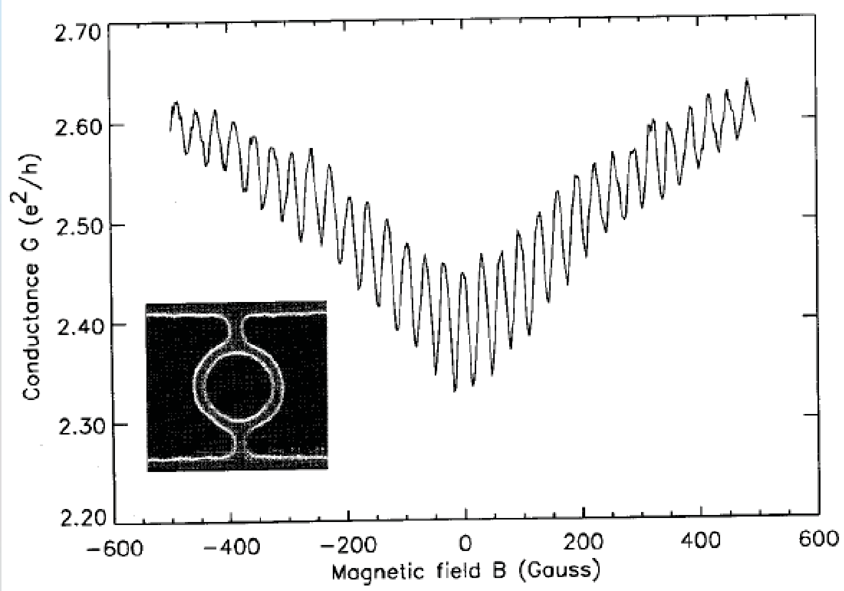
Shubnikov-de Haas oscillations and the quantum Hall effect. We look at a measurement of the longitudinal and the Hall resistance (R_{xx} and R_{yy}, respectively), of a two dimensional electron gas, as a function of a magnetic field applied perpendicular to the plane of the quantum film. The experiment has been performed at a temperature of 100 mK.

The Hall resistance is *quantized* in units of $h/2e^2$.

Phase coherence

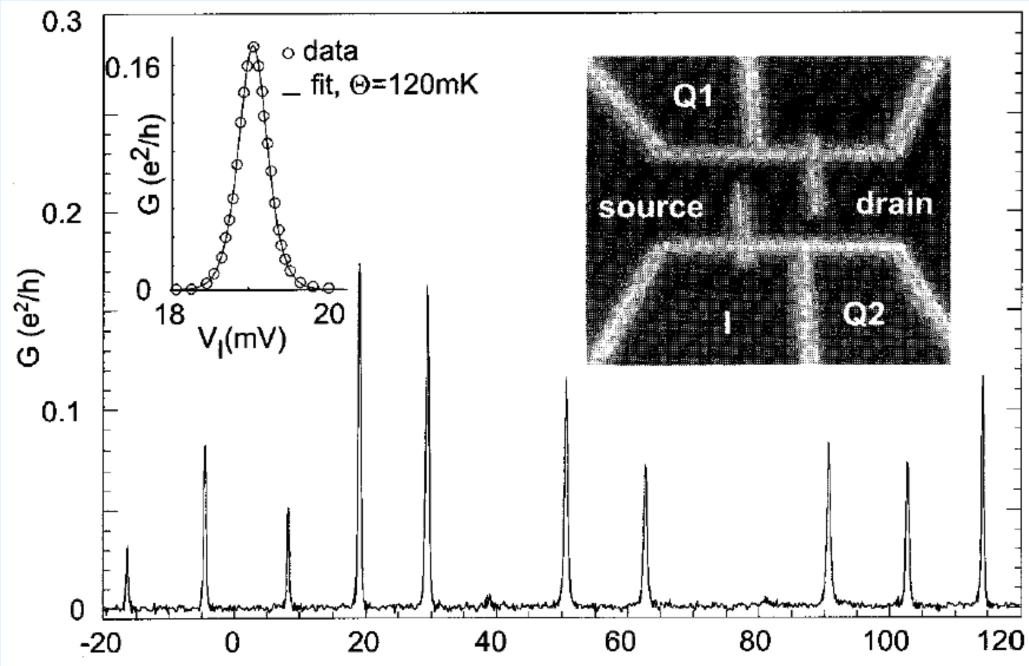
At low temperatures

$$\ell_\phi \geq 100\ \mu m$$



The resistance of a small ring with a diameter of about 1 micron (the light gray areas in the inset) as a function of a magnetic field applied perpendicular to the ring plane shows periodic oscillations, known as *Aharonov-Bohm oscillations*.
They indicate that a significant fraction of the electrons traverse the ring phase coherently.

Single-electron tunneling and quantum dots



The right inset shows again the surface topography of a semi-conductor with a two dimensional electron gas underneath.
The bright lines enclose a small island. It is coupled to source and drain via two quantum point contacts, forming tunnel barriers for the electrons. The barriers are tuned by adjusting the voltages at the gates Ql and Q2.

The main figure shows the conductance through the island as a function of the gate voltage V_I applied to region I.

V_I tunes the potential of the island. The conductance peaks indicate that only for a particular island potential, electrons can be transferred between the island and the leads.

The left inset shows a fit to a function one would expect for peaks that are governed by thermal smearing of the Fermi function.

Plan of the course on nanophysics given at the University of Oslo

Lectures

- Brief update of conventional solid state physics
  - Crystal and band structures, diffusive transport, scattering mechanisms, screening
- Surfaces, interfaces and layered devices
- Experimental aspects
  - Materials growth, sample fabrication and characterization
- Mesoscopic physics
  - Two-dimensional electron gas
  - Quantum wires and quantum point contacts
  - Electron phase coherence
  - Single-electron tunneling device
  - Quantum dots
  - Mesoscopic superconductor and hybrid devices
- New directions in electronics (overview)
  - Spintronics, molecular electronics, nanomechanics, devices for quantum computation.

http://folk.uio.no/yurig/Nanotechnology/MEF5010.html

Topics presented by students

1. Single crystal growth

   Growth of layered structures, epitaxy - liquid phase epitaxy (LPE), molecular chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), magnetron sputtering, etc

2. Lateral patterning (electron beam patterning) and bonding

3. Sample characterization

   Electron microscopy (TEM, SEM)

   Tunneling microscopy (STM)

   Secondary ion mass spectroscopy (SIMS)

   X-ray spectroscopy

   Elements of cryogenics

Conclusion

Christopher Columbus wins the Spanish monarchs' support – one of the first research grants

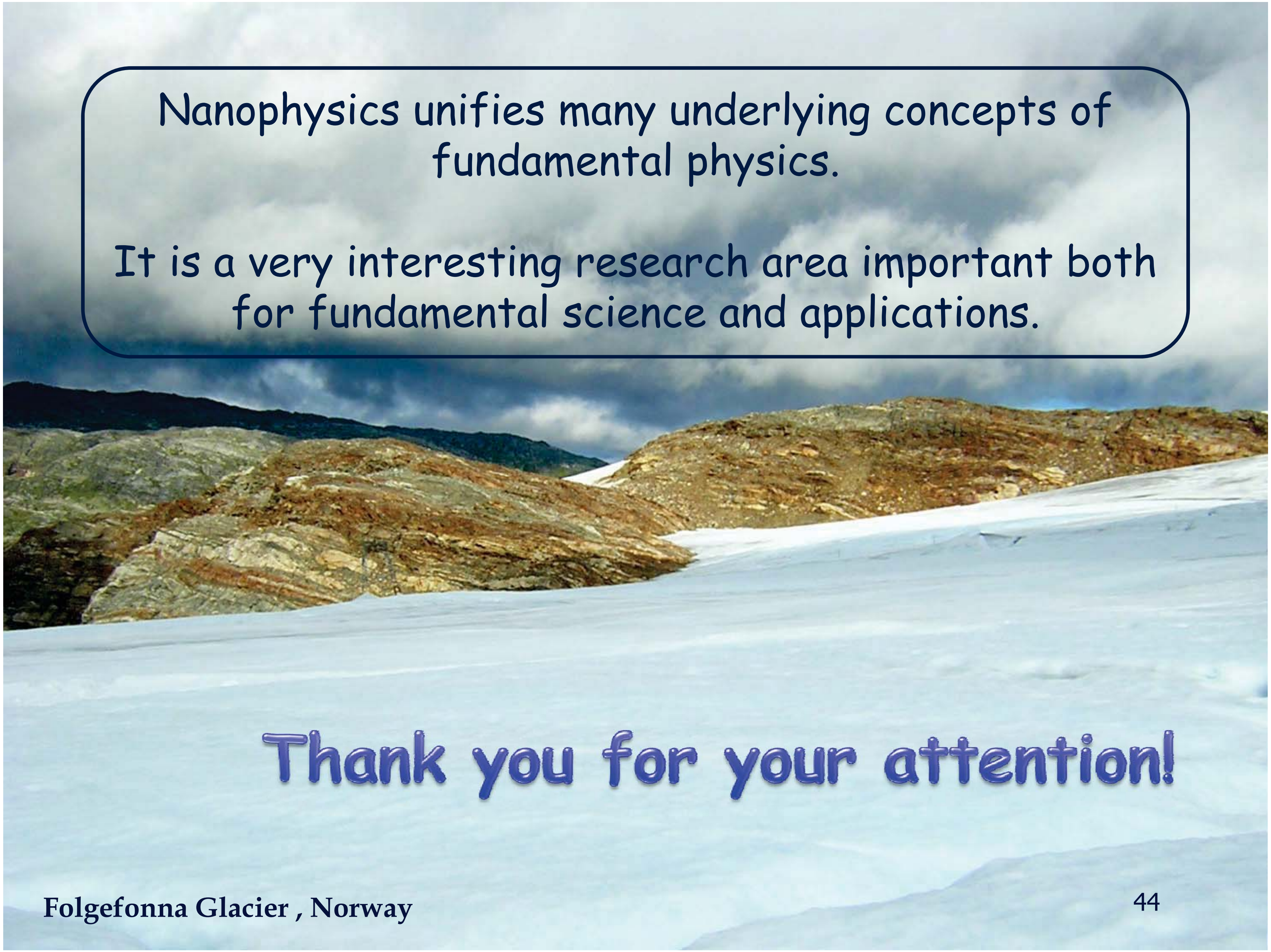
In 1484 Columbus submitted his theories to John II, king of Portugal, petitioning him to finance a westward crossing of the Atlantic Ocean.

His proposal was rejected by a royal maritime commission because of his miscalculations and because Portuguese ships were already rounding Africa.

In Spain, as in Portugal, a royal commission rejected his plan.

Columbus continued to seek support, and in April 1492 his persistence was rewarded: Ferdinand V, King of Castile, and Queen Isabella agreed to sponsor the expedition.

Today nobody disputes the fact the discovery of the New World has both fundamental and practical importance.


Nanophysics unifies many underlying concepts of fundamental physics.
It is a very interesting research area important both for fundamental science and applications.
Thank you for your attention!
Folgefonna Glacier , Norway