Radboud Universiteit Nijmegen

Science, Creativity, Graphene

Mikhail Katsnelson

What is science and what is technology?

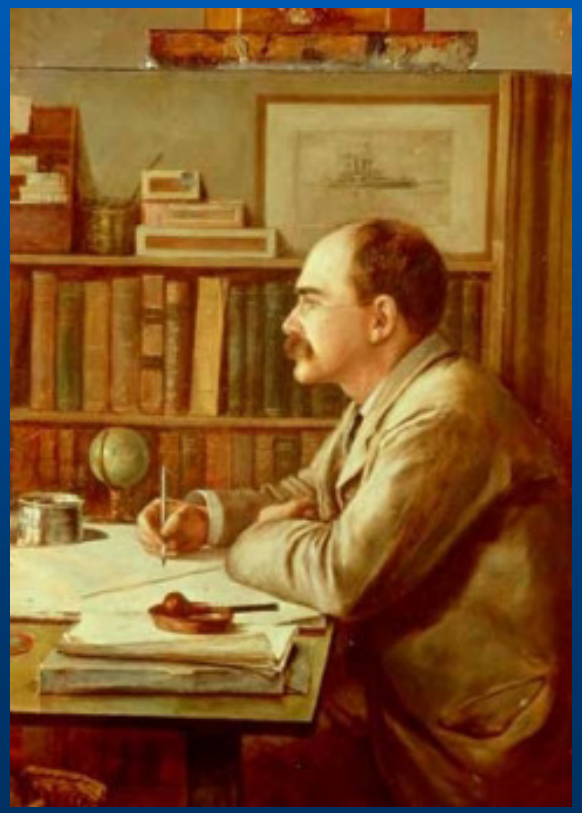
The aim of technology: to use

The aim of science: to understand

Can wrong idea be practically useful? – yes!

Why had the plague not broken out at the blacksmith's shop in Munday's Lane? Because, as I've shown you, forges and smithies belong naturally to Mars, and, for his honour's sake, Mars 'ud keep 'em clean from the creatures of the Moon… '"Eureka, good people!" I cried, and cast down a dead mill-rat which I'd found. "Here's your true enemy, revealed at last by the stars." "If you would stay the plague, take and kill your rats." None the less, the plague ceased and took off from the morning of the day that Mars enlightened me by the Lower Mill.'

(R. Kipling, A Doctor of Medicine)



Space travels

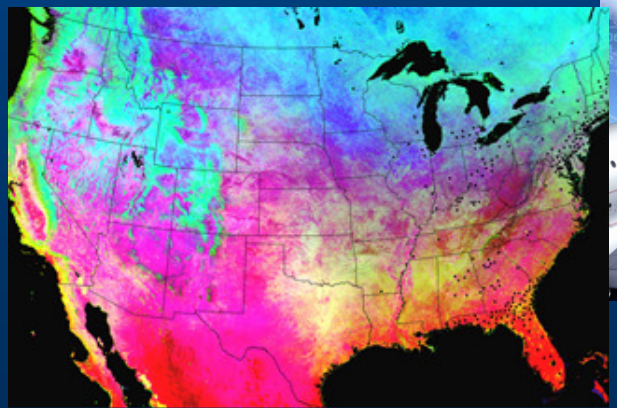
Konstantin Tsiolkovsky

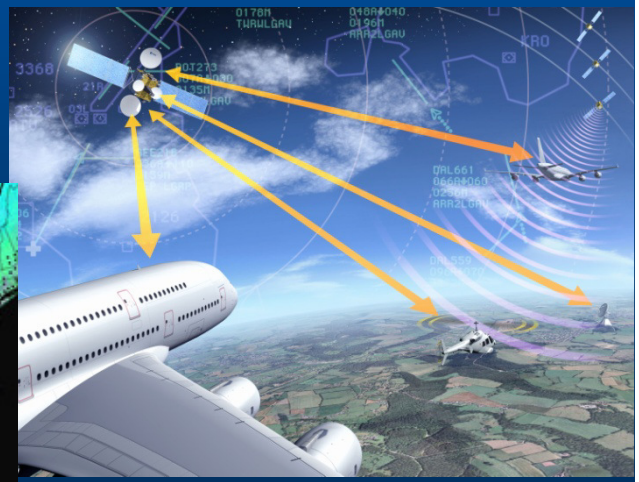
"Russian Cosmism"
Nikolai Fedorov
The aim: physical immortality and resurrection of the dead
Need a lot of space!
Motivation for space travels...

Brisbane Planetarium

Practical use of satellites

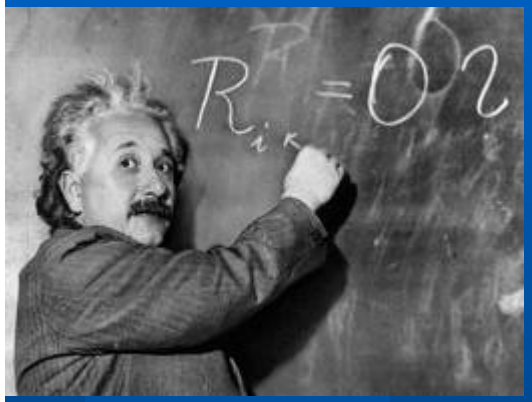
Navigation, weather forecast, communications, astronomy... Not talking on military applications



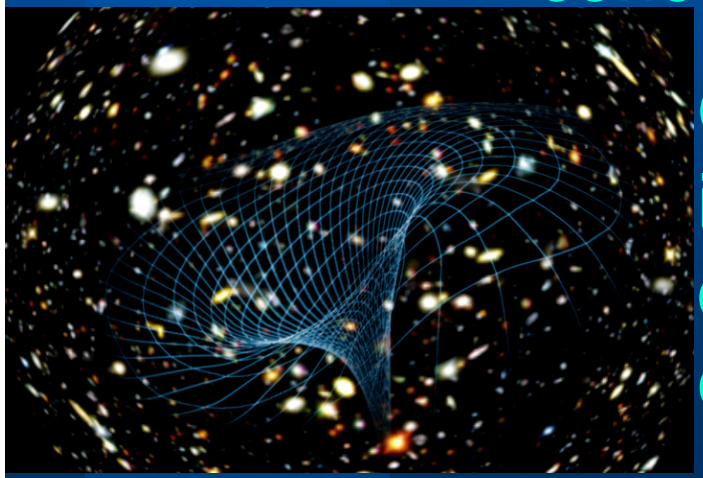


Can correct idea be practically useless?

Well... for sure (how can we use Higgs bosons or gravitational waves discovered very recently)? But...



Einstein's general theory of relativity (one of the most abstract physical concepts)



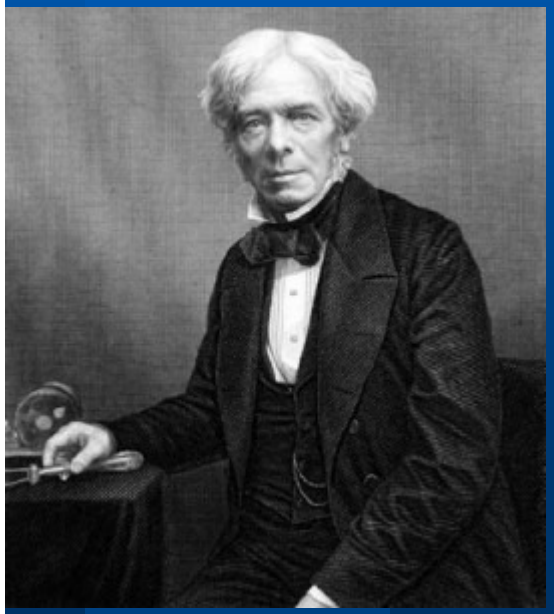
Gravitation is the curvature of space-time

Time is slowing down by gravity

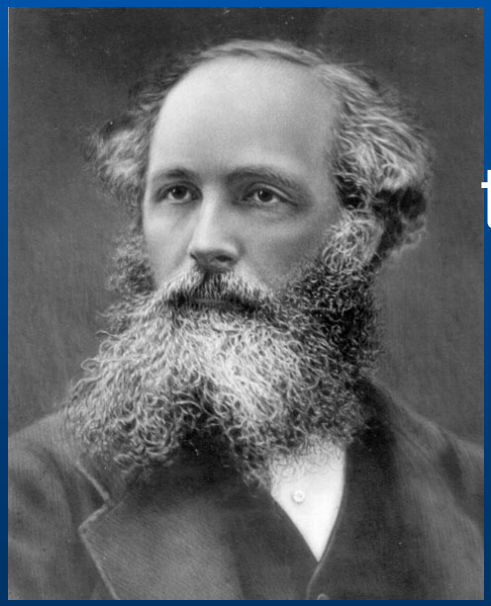
Should be taken into account in GPS!

Example: classical electrodynamics

From a long view of the history of mankind - seen from, say, ten thousand years from now - there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade (R. P. Feynman)



Faraday



Maxwell

Faraday and Maxwell together have probably justified all expenses for fundamental science for thousands years in advance

Science and technology II

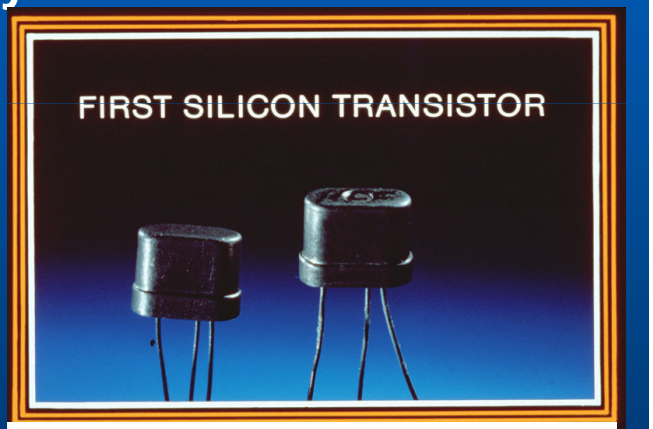
If we do not know whether the problem is solvable or not, it is science; if we are sure that we can do it but do not know whether it is worth to do or not – it is technology

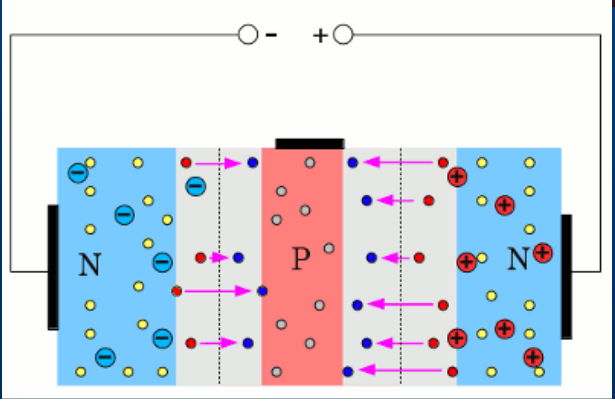
Science opens ways for dramatically new solutions

Triode (electronic vacuum tube)

Based on classical physics

Transistor is based on quantum physics – totally new concept of nature

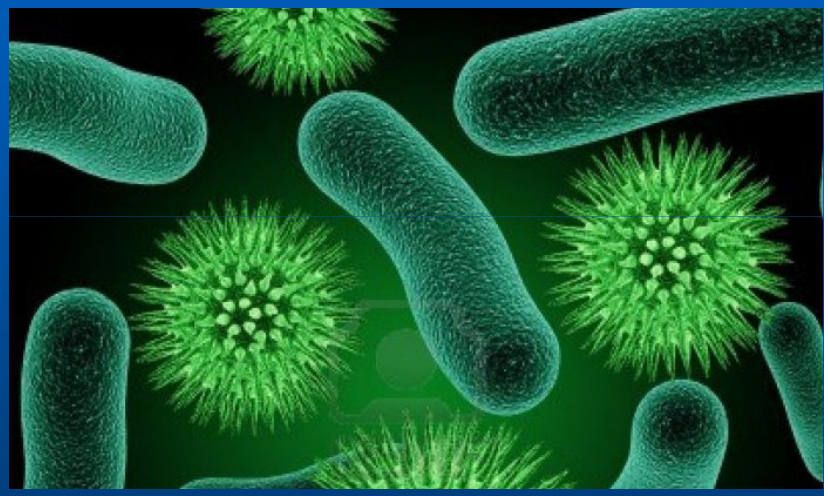




Science is necessary for survival of humankind

Agriculture ("green revolution")
Medicine (new antibiotics: arms race with bacteria)

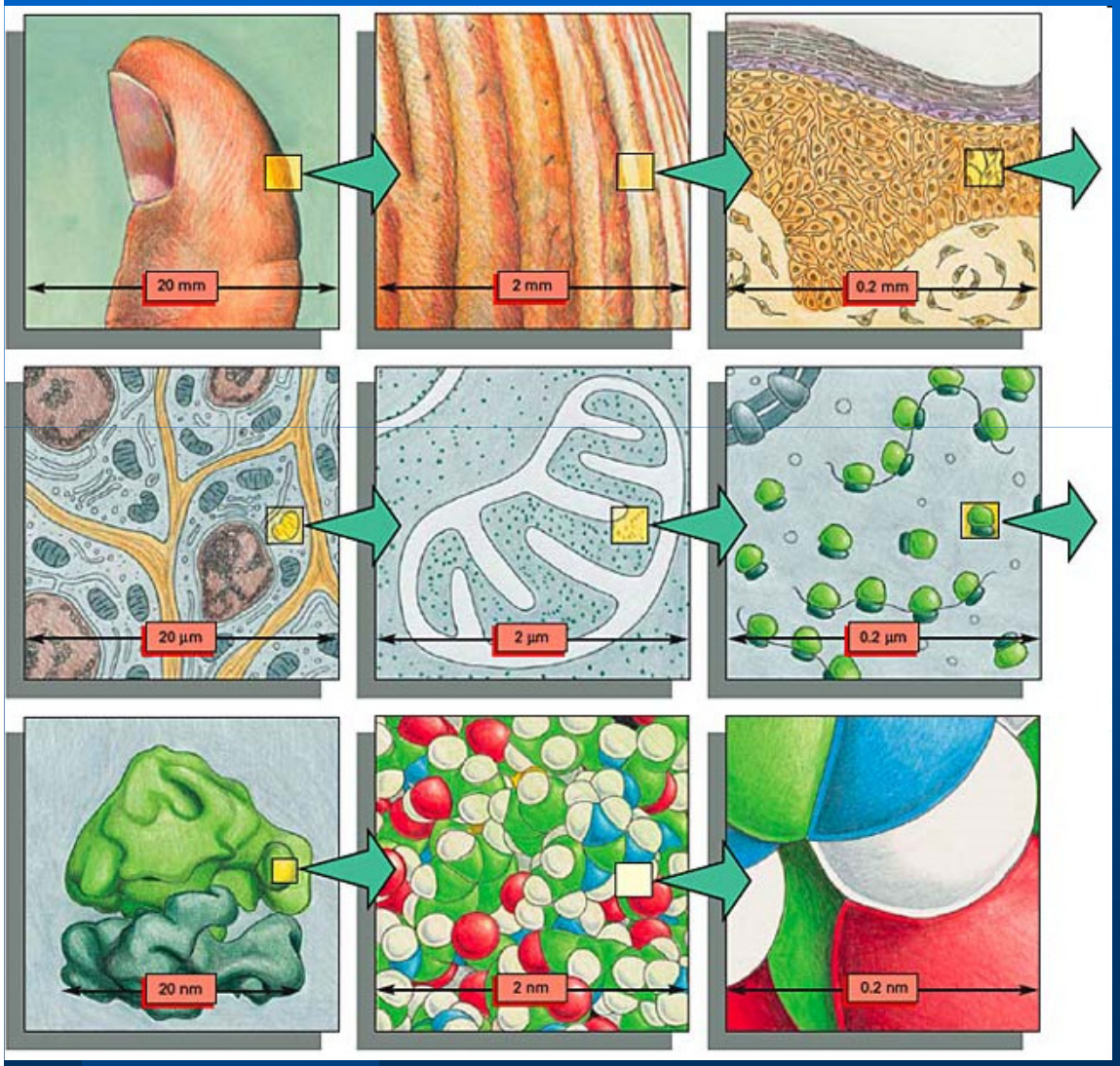
We cannot just stop: too many will die



Our society is crucially dependent on communications, transport, computers... well... weapons...

Very important to know how science works

Structural levels of matter



Hierarchy of levels

Shall we first make a list of the “most fundamental laws” and then apply them using A Very Big Computer?!

How our science works?

Knowledge begins, so to speak, in the middle, and leads into the unknown - both when moving upward, and when there is a downward movement. Our goal is to gradually dissipate the darkness in both directions, and the absolute foundation - this huge elephant carrying on his mighty back the tower of truth - it exists only in a fairy tales (Hermann Weyl)

What does it mean for condensed matter physics and materials science?

Everything follows from quantum mechanics plus electrodynamics; QED is enough to explain all properties of matter around us

$$\gamma^\alpha(\partial_\alpha - ieA_\alpha)\psi + im\psi = 0 \quad \text{where} \quad \alpha = 0, \ldots, 3$$

$$F_{\alpha\beta} = A_{\beta,\alpha} - A_{\alpha,\beta}$$

$$\partial^\alpha F_{\alpha\beta} = -4\pi e j_\beta$$

$$\text{where} \quad j_\alpha = \overline{\psi}\gamma_\alpha\psi.$$

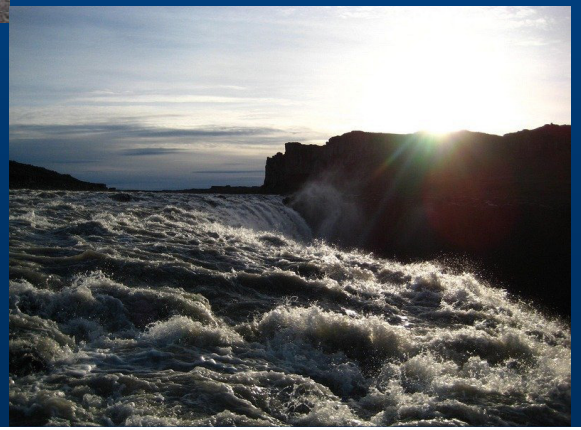
That is all. Please tell me why iridium is brittle and platinum is ductile, copper is red and silver is white, iron is ferromagnetic and vanadium is not... Not talking on biochemistry and biophysics!

Does science stop when basic laws are known?

$$\nabla \cdot u = 0$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = f + \mu \nabla^2 u - \nabla p$$

Navier-Stocks equations:
Turbulence is here!
Can you explain this?



Is fundamental physics fundamental?

Classical thermodynamics is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts (A. Einstein).

The laws describing our level of reality are essentially independent on the background laws. I wish our colleagues from true theory (strings, quantum gravity, etc....) all kind of success but either they will modify electrodynamics and quantum mechanics at atomic scale (and then they will be wrong) or they will not (and then I do not care). Our way is down.

How to pass from known basic laws of nature to understanding all richness and diversity of the world around us?

The aim of science: Understanding

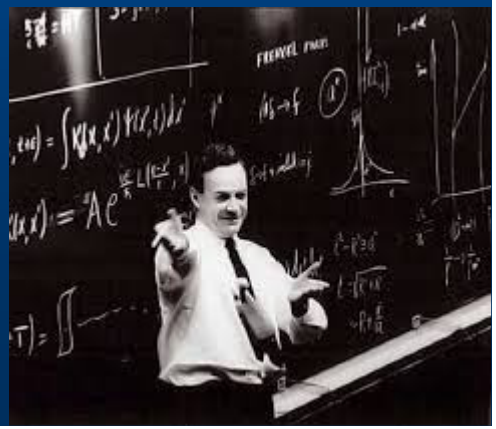
Duality of understanding and knowledge

Newton laws... Rotation...
Air resistance... I know this stuff
but the result will be... well...

He does not know (?!) Newton Mechanics – but it works! He feels (=understands) what to do

I think I can safely say that nobody understands quantum mechanics

(R. P. Feynman)



Scylla and Charybdis

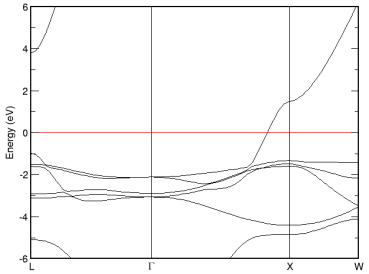
Understanding “in general”

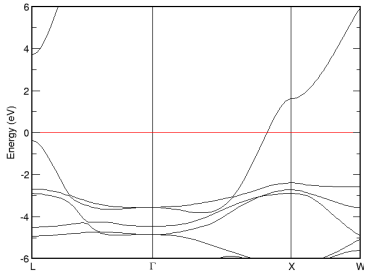
Everything is from water/fire/earth/gauge fields/quantum space-time foam/strings...

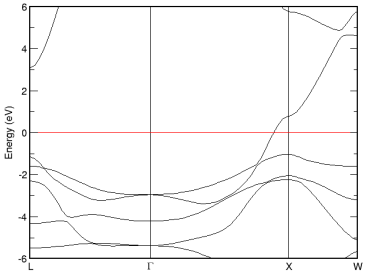
and the rest is your problem.

But why silver is white, copper is red an gold is yellow?

Density functional calculations







Cu Ag Au

Can we take it as an explanation?

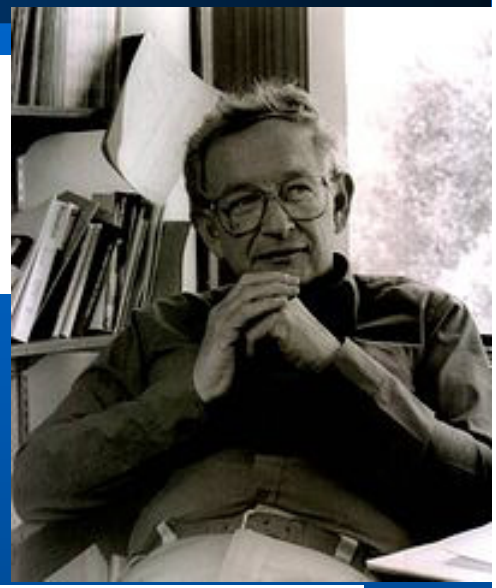
Scylla and Charybdis II

Local moments and localized states

P. W. Anderson

Reviews of Modern Physics, Vol. 50, No. 2, April 1978

(Nobel lecture)



shall soon discuss. Very often such a simplified model throws more light on the real workings of nature than any number of *ab initio* calculations of individual situations, which even where correct often contain so much detail as to conceal rather than reveal reality. It can be a disadvantage rather than an advantage to be able to compute or to measure too accurately, since often what one measures or computes is irrelevant in terms of mechanism. After all, the perfect computation simply reproduces Nature, it does not explain her.

A normal way of doing theoretical physics

Combining elements: a (known) method A, apply to calculate a property B (was caclulated earlier but in another way), consider a system C (was calculated earlier for other systems)...

You can be taught to do it

Dramatically new ideas (e.g., gravity as a curvature of space-time): very rare, very important and we do not know how it happens)

It may be useful to know how people did it before (most of physicists are quite ignorant in history of physics) but you are not guaranteed...

Working with a space of ideas

Mathematics is the *art* of giving the same name to different things (H. Poincare)

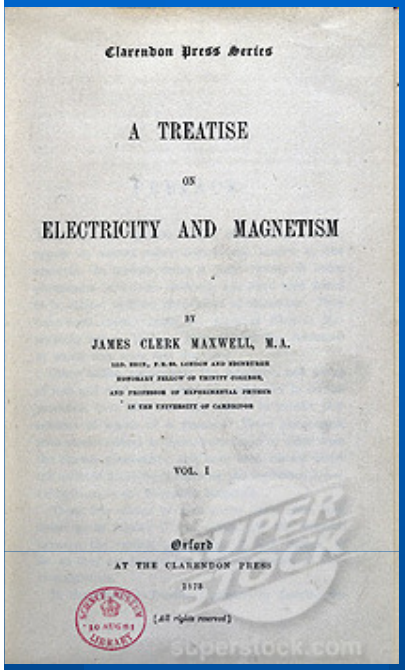
Like in a good book or a good movie: a lot of intrinsic relations, cultural references...

Analogy: a quantum computer vs classical

Working with N elements or with the whole “Hilbert space” (2^N combinations)

Graphene: coupling together solid state physics, soft matter, relativistic quantum mechanics and even gravity

Correct theories from wrong assumptions


Clarendon Press Series

A TREATISE

ON

ELECTRICITY AND MAGNETISM

BY

JAMES CLERK MAXWELL, M.A.

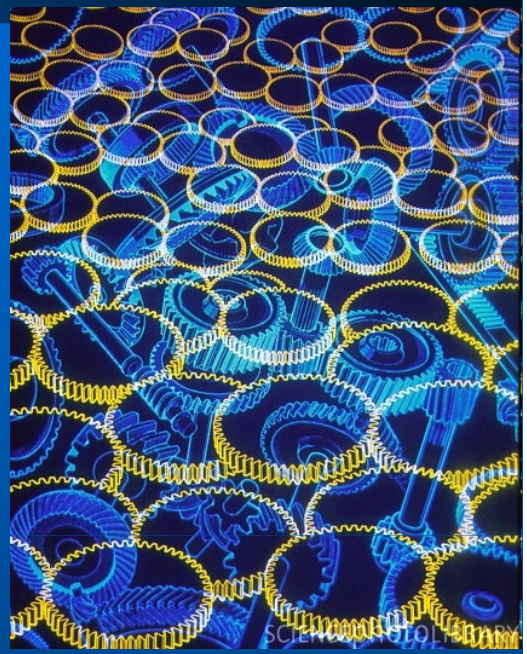
VOL. I

Oxford

AT THE CLARENDON PRESS

Electromagnetic fields as deformations in ether; gears and wheels

We do not believe now in mechanical models for electromagnetic field but Maxwell equations are correct



Also: Dirac equation (relativistic wave equation is not necessarily the first-order equaiton as Dirac postulated)

Landau theory of superfluidity of helium (he did not take into account Bose statistics of helium atoms which is crucially important)

Theoretical physics as a variety of mistique experience

Beloved, believe not every spirit, but try the spirits whether they are of God (1 John 4:1)

Ye shall know them by their fruits. Do men gather grapes of thorns, or figs of thistles? (Matthew 7:16)

Fruits: to predict something correctly (like Maxwell electromagnetic waves, Dirac – positron, Landau – second sound in superfluid helium...)

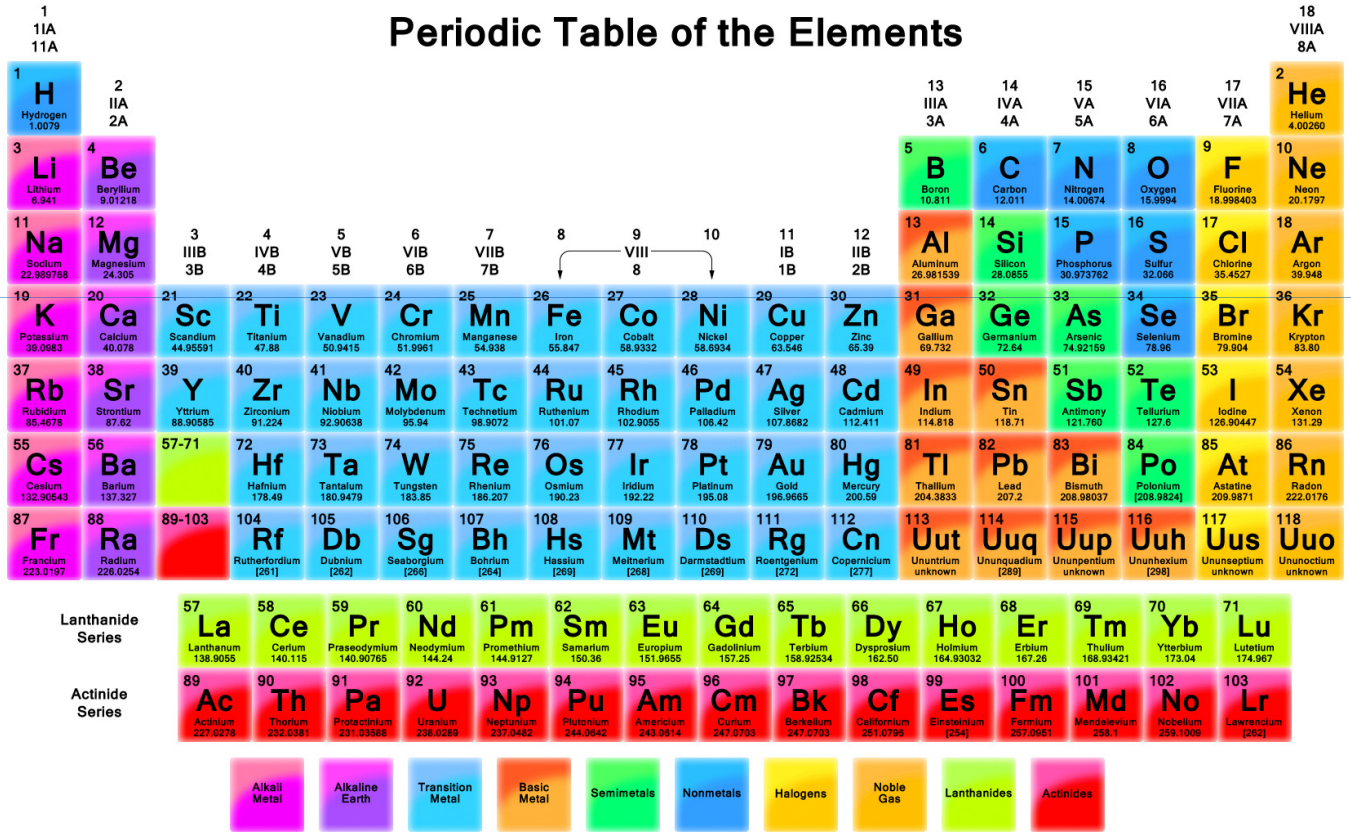
Top pleasure and top dream for a theoretician

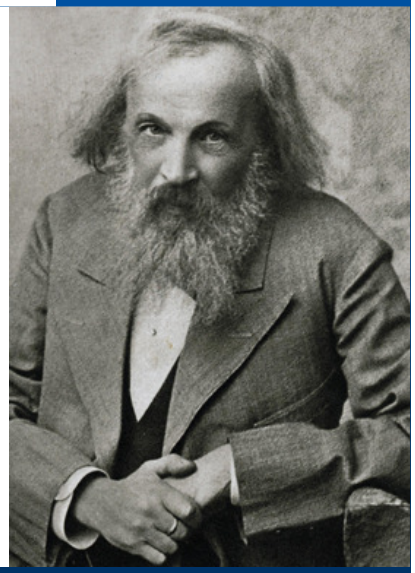
Graphene

1. Klein tunneling
2. Pseudomagnetic fields due to deformations
3. Relativistic collapse at a supercritical charge

Periodic Table

Can we understand something elementary?





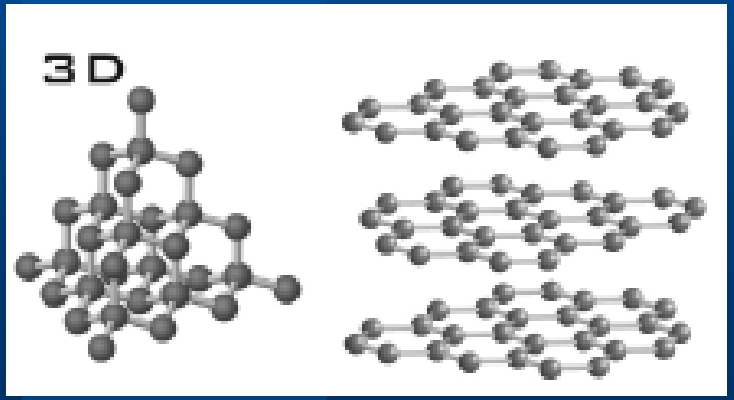
D. I. Mendeleev

Carbon, element #6

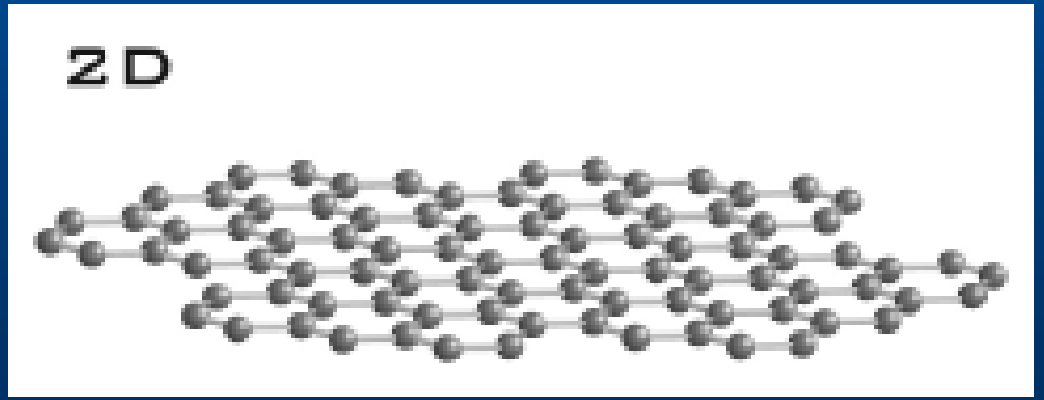
Diamond

Graphite

Determined by arrangement of carbon atoms

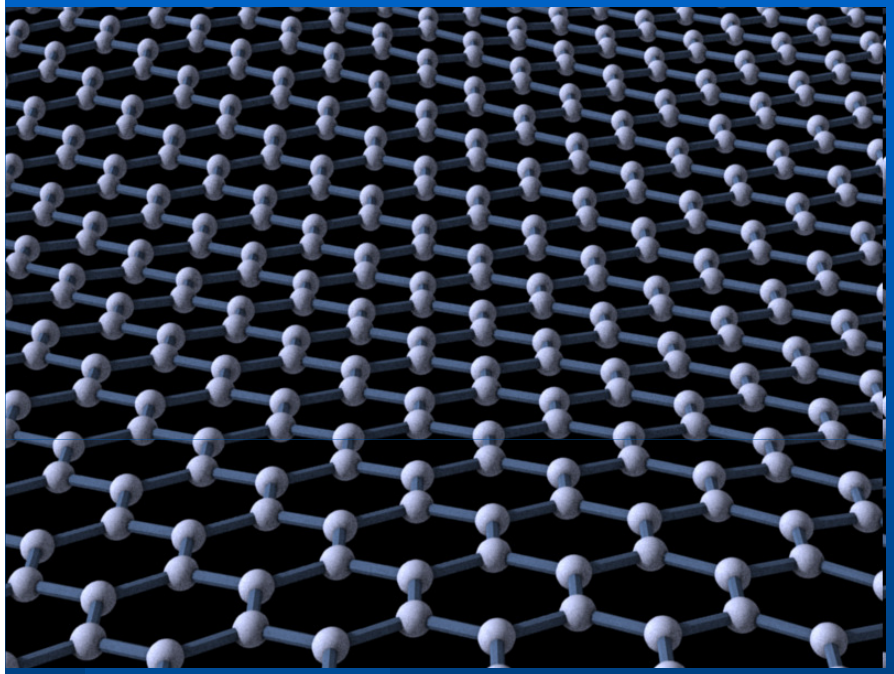


Diamond, Graphite



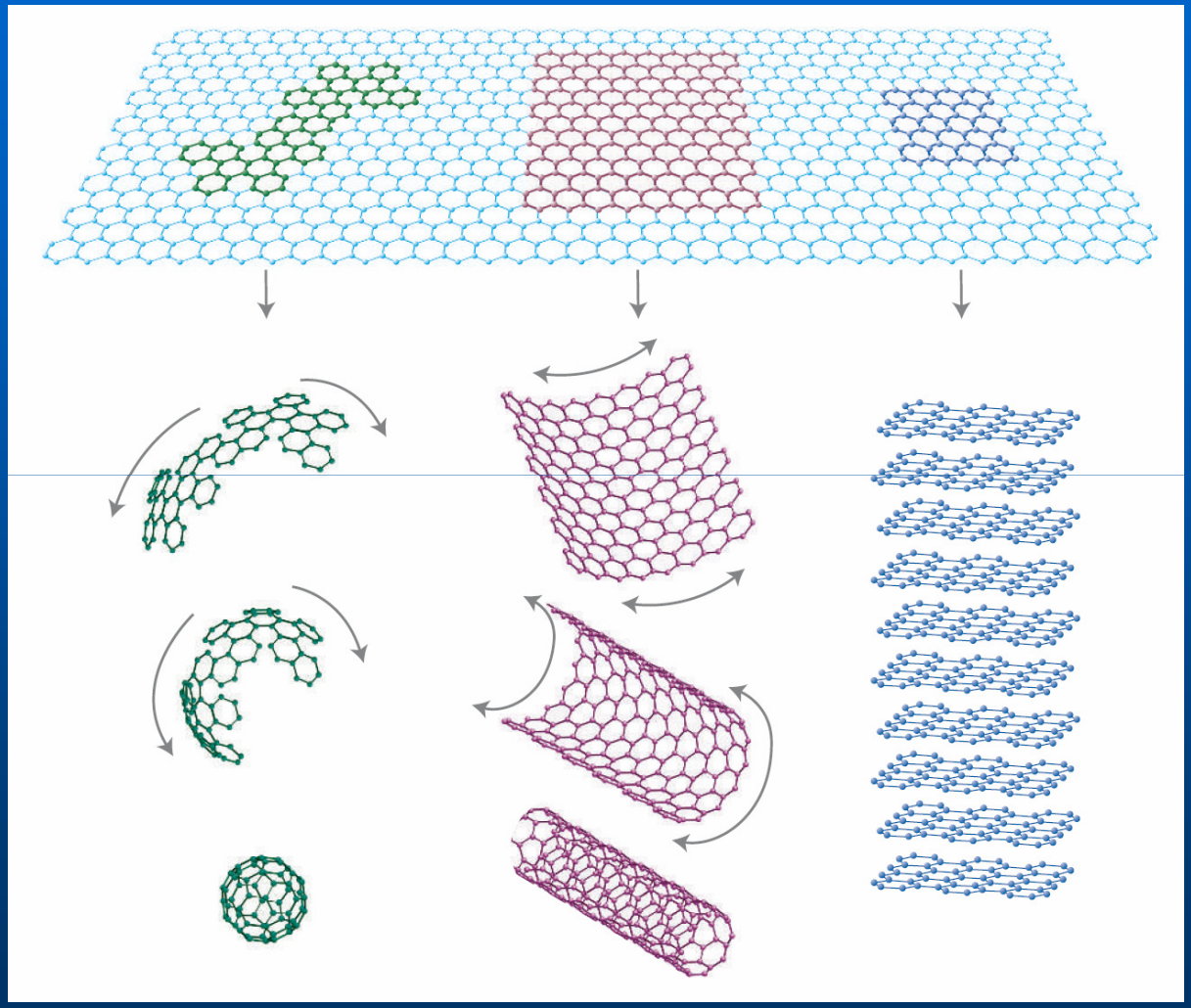
Graphene: a prototype 2D crystal

Honeycomb



Hexagonal crystal lattice

Mother of all graphitic forms



Fullerenes Nanotubes Graphite

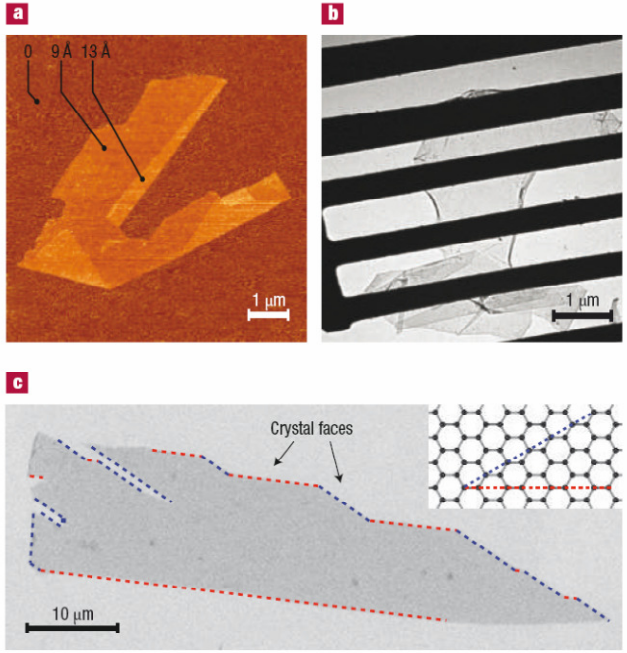
Discovery of graphene

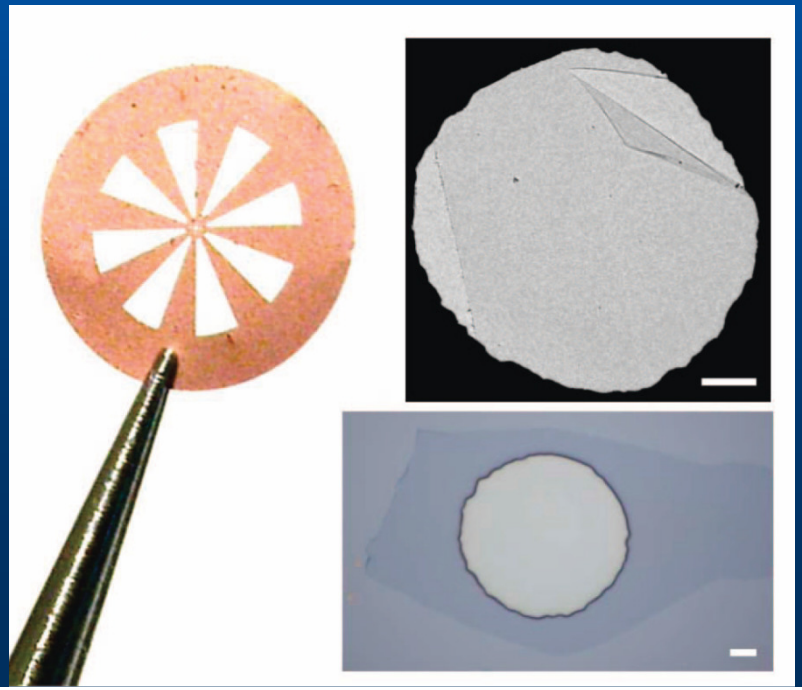
Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

22 OCTOBER 2004 VOL 306 SCIENCE

Andre Geim and Kostya Novoselov
Nobel Prize 2010

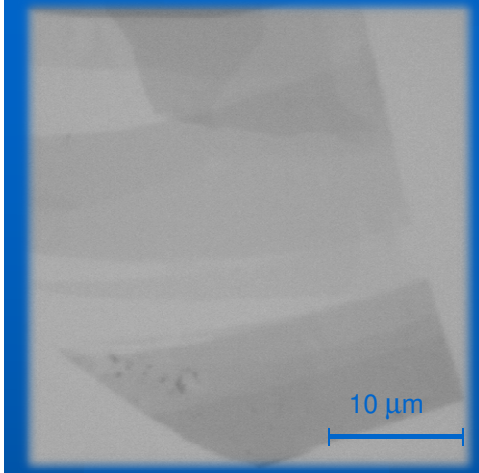


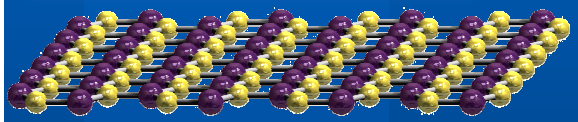


Beyond Graphene

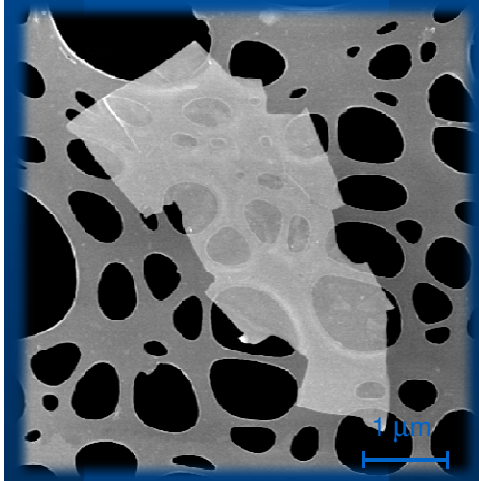
2D crystals from other layered materials

2D boron nitride in optics



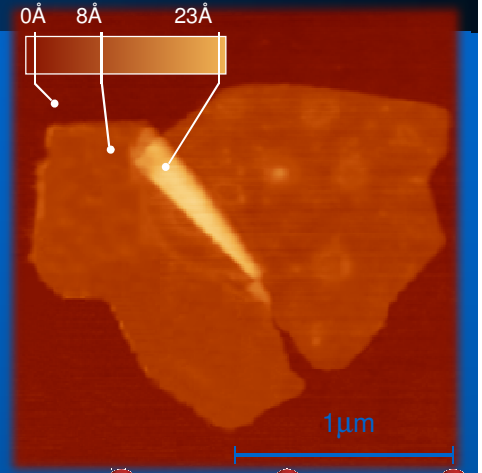


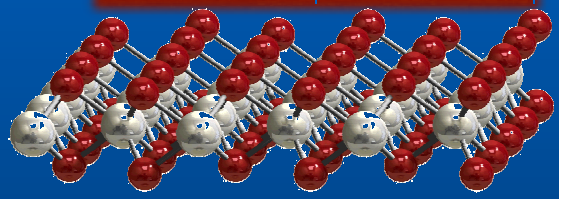
Novoselov et al
PNAS (2005)

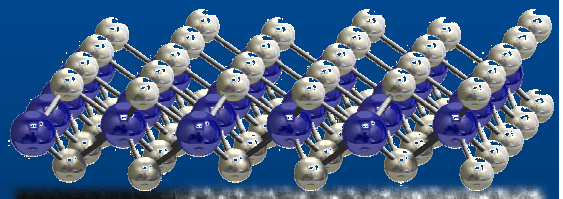


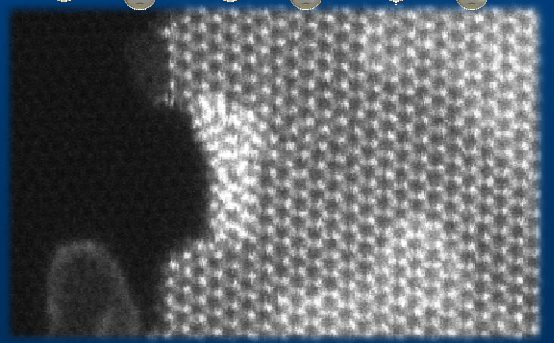
2D $Bi_2Sr_2CaCu_2O_x$ in SEM

2D $NbSe_2$ in AFM





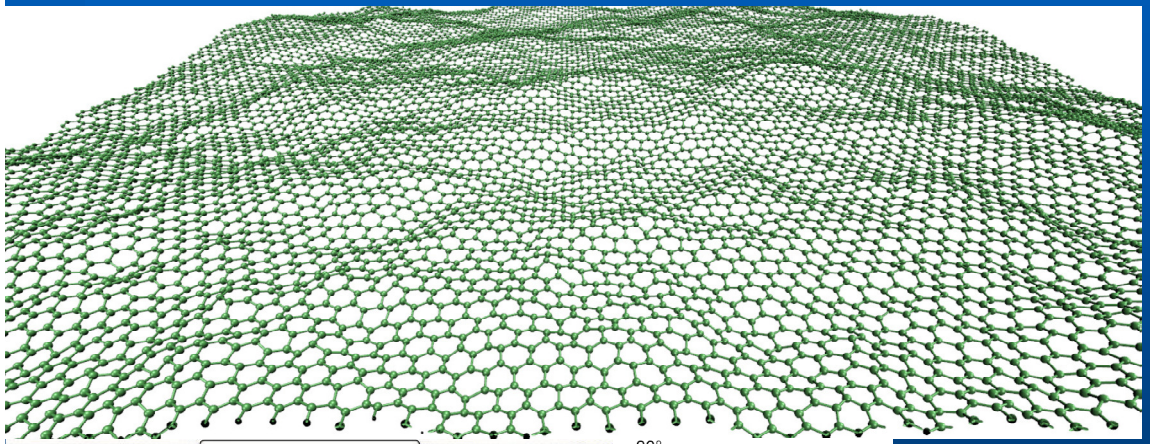




2D MoS_2 in TEM

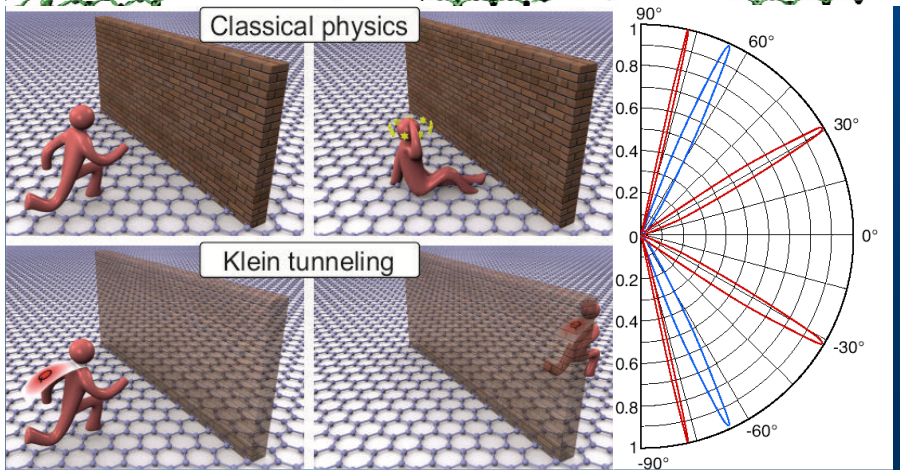
Why graphene is interesting?

1. *Applications (modern electronics is 2D, bulk is ballast)*
2. *Prototype membrane (new drosophila for 2D statistical mechanics)*
3. *CERN on the desk (mimic high energy physics)*



Ripples

Fasolino, Los & MIK,
Nature Mater. 6, 858 (2007)



Klein tunneling

MIK, Novoselov, Geim, Nature Phys.
2, 620 (2006)

How to make graphene transistor?

Conventional transistor: Cannot be locked due to Klein tunneling

Solution: a “vertical geometry”

Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures

L. Britnell,[1] R. V. Gorbachev,[2] R. Jalil,[2] B. D. Belle,[2] F. Schedin,[2] A. Mishchenko,[1] T. Georgiou,[1] M. I. Katsnelson,[3] L. Eaves,[4] S. V. Morozov,[5] N. M. R. Peres,[6,7] J. Leist,[8] A. K. Geim,[1,2]* K. S. Novoselov,[1]* L. A. Ponomarenko[1]*

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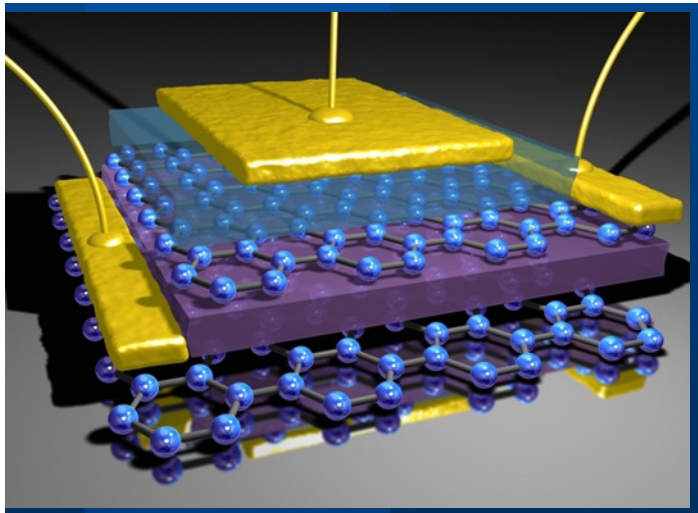
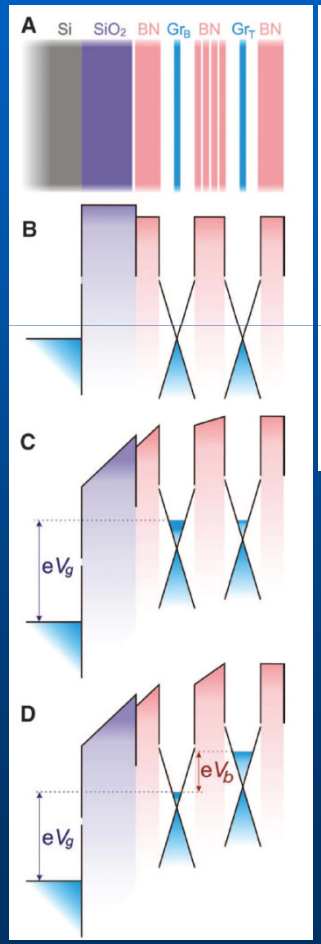
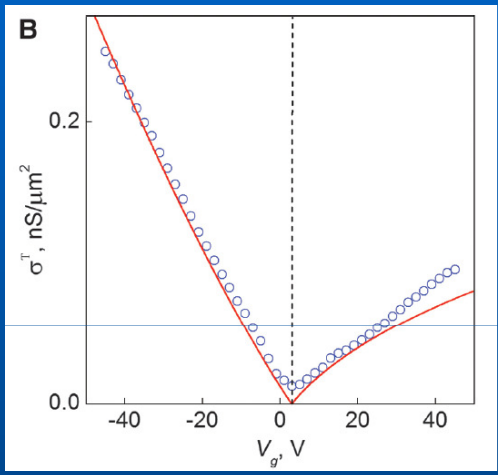


Graphene
Spacer
Graphene



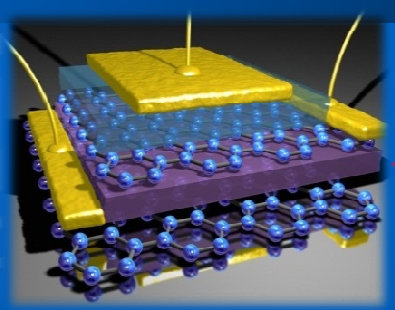


Control of tunneling

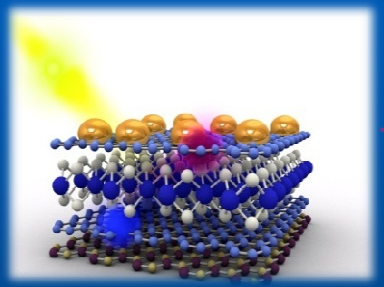
Example of artificial heterostructures

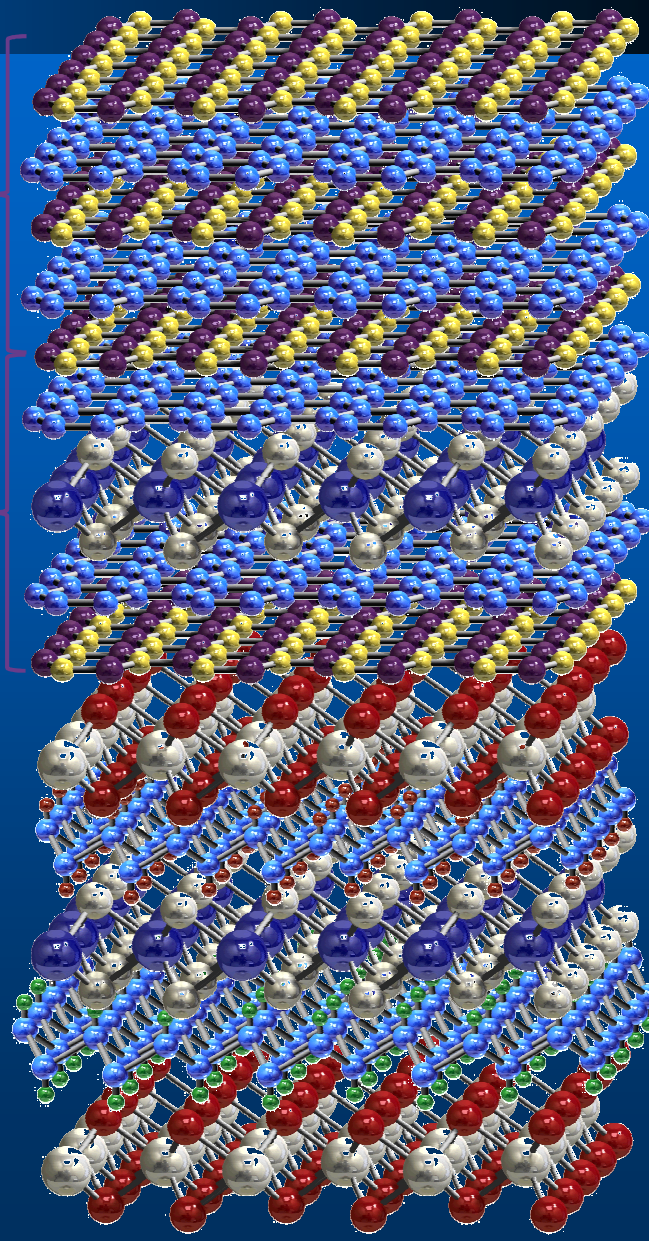
Heterostructures Based on 2D Crystals

Tunnelling Transistor
Manchester Science '12
Manchester Nature Nanotechnology '13
on/off >10^6
suitable for modern electronics



Solar cells
Manchester Science '13
large quantum efficiency

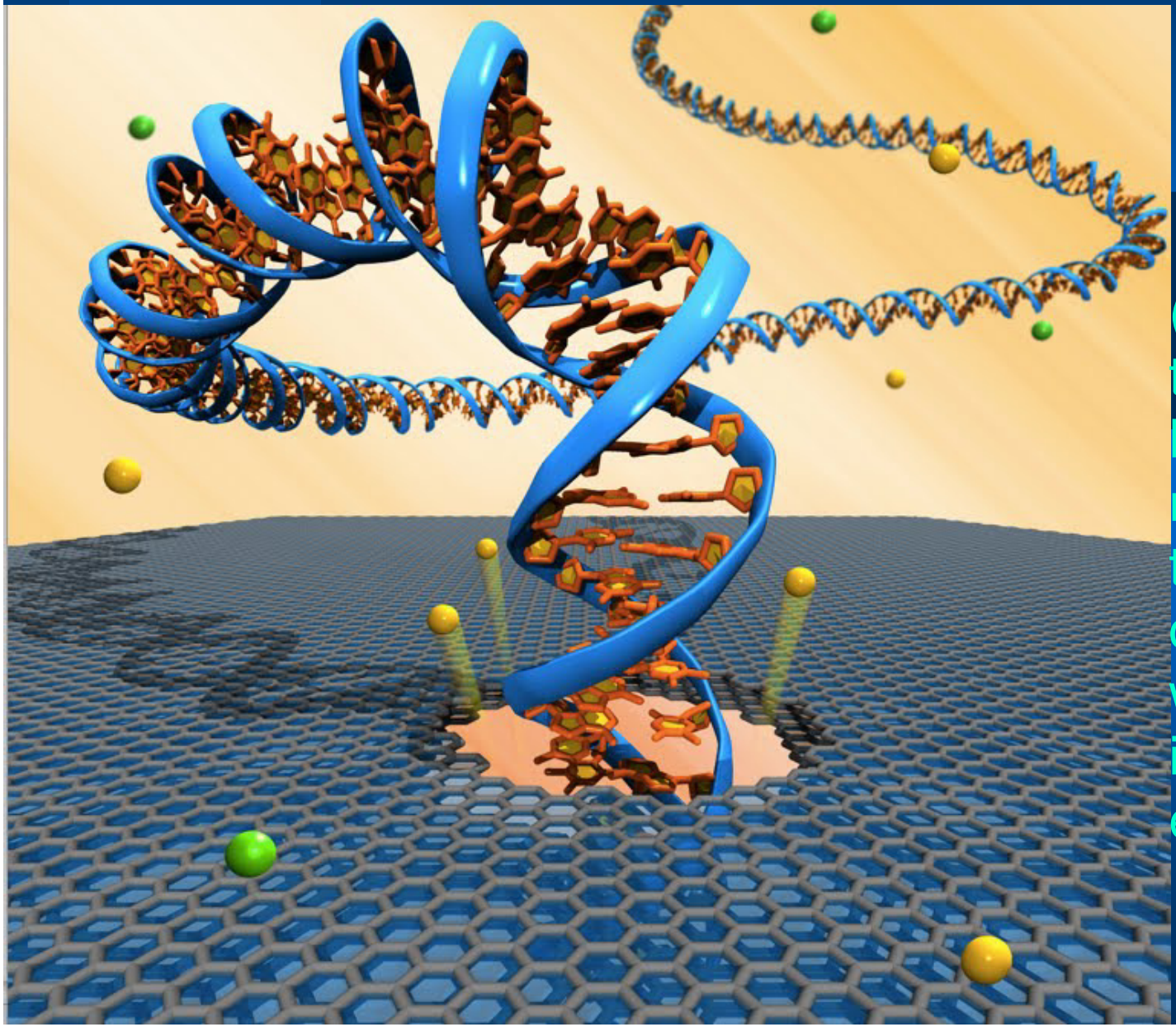




Large number of 2D crystals – infinite functionality
Many different devices possible

Layer-by-Layer Material Engineering

Unexpected applications (e.g., biology)



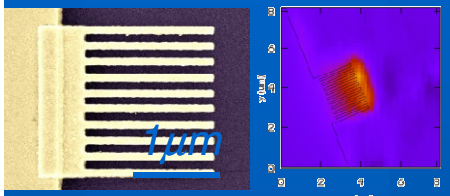
DNA sequencing

(move DNA through the hole in graphene, measure tunneling conductivity which is individual for each nucleotide)

All Major Applications are Realistic

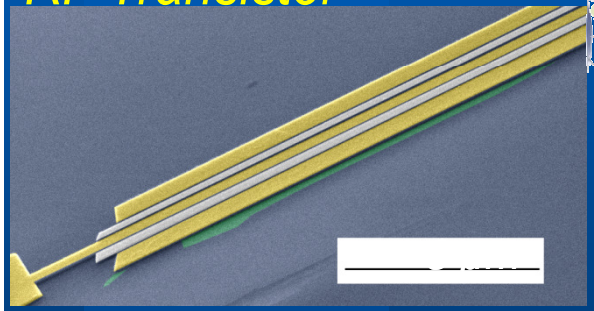
Photovoltaics

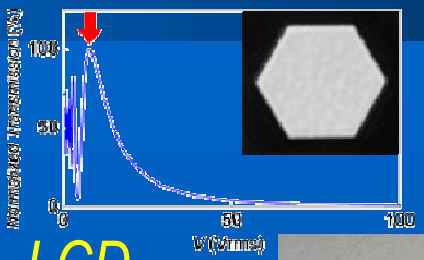
Photodetectors



Electronics

RF Transistor

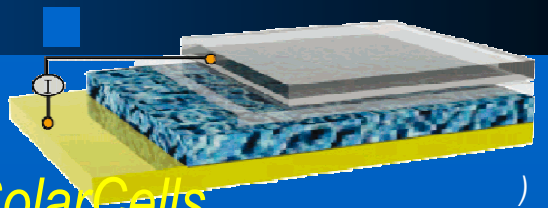




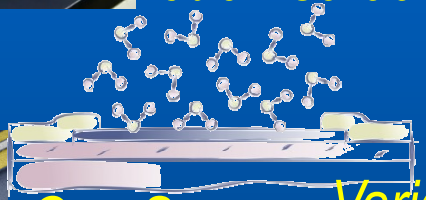
LCD

Touch-screens

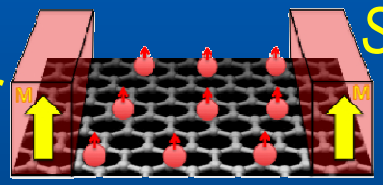
Tactile Display



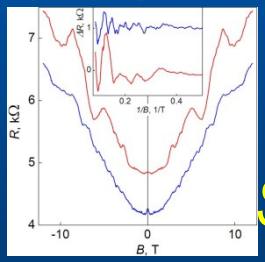
Solar Cells



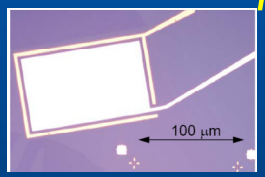
Gas Sensor



SpinValve



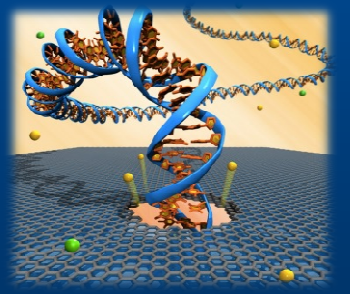
Variable Capacitor



Strain Gauge

Healthcare and Bio

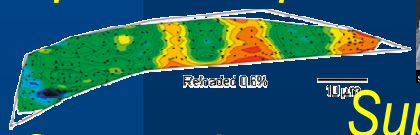
DNA Sequencing



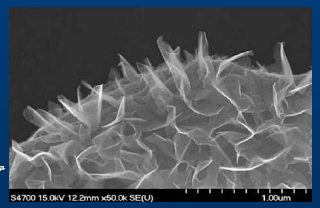
Composite Materials

Mechanically Strong;
Conductive; Optically Active

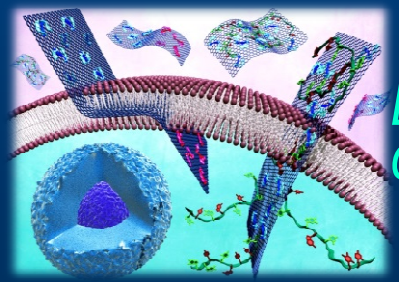
Graphene Paper



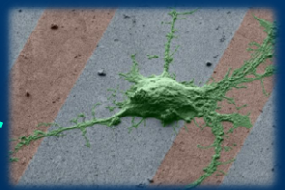
Composites



Supercapacitors



Drag delivery



Sensor