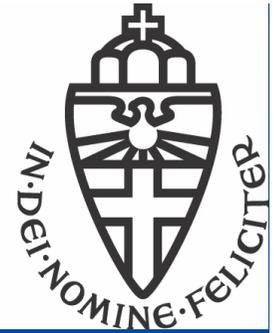


Radboud Universiteit Nijmegen



*Science, Creativity,  
Graphene*

*Mikhail Katsnelson*

# *What is science and what is technology?*

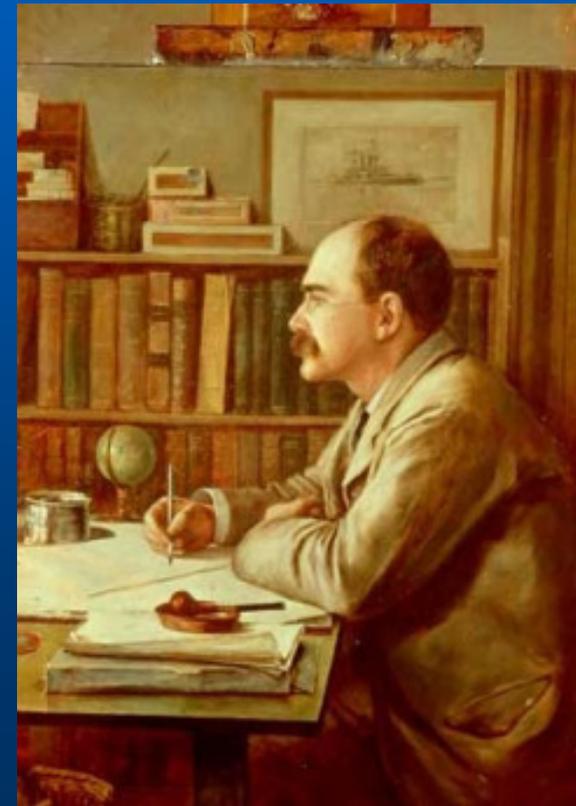
The aim of technology: to use

The aim of science: to understand

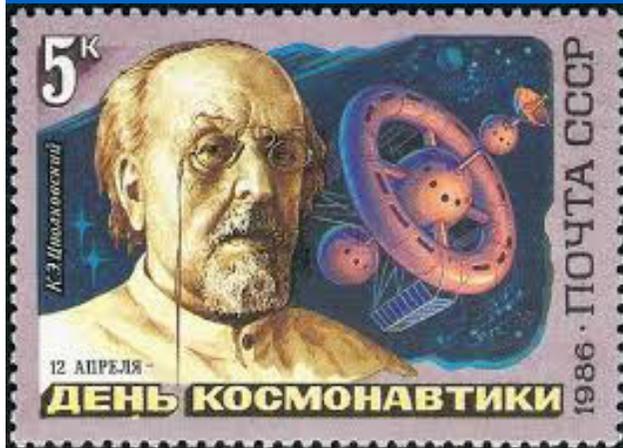
Can wrong idea be practically useful? – yes!

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!

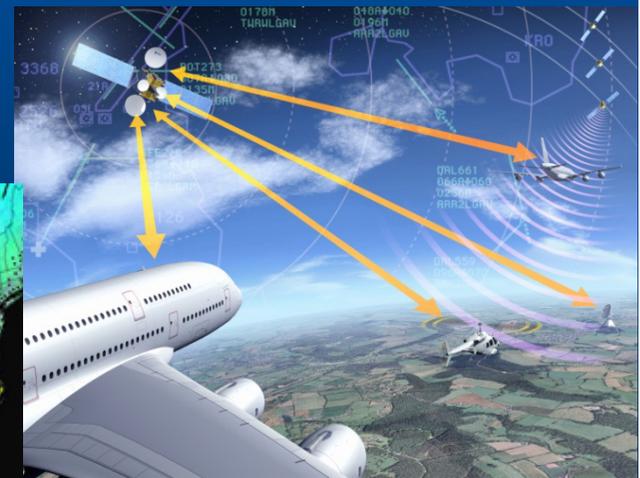
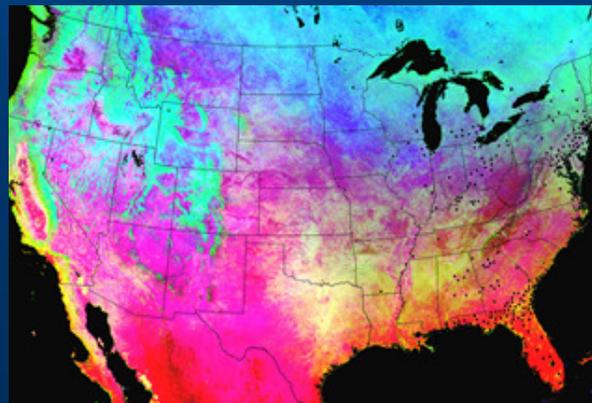
Motivation for space  
travels...



Brisbane  
Planetarium

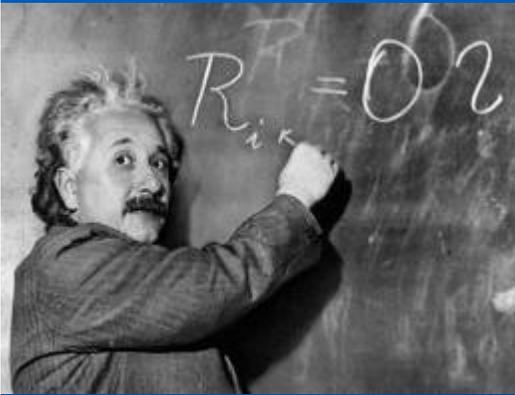
## Practical use of satellites

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

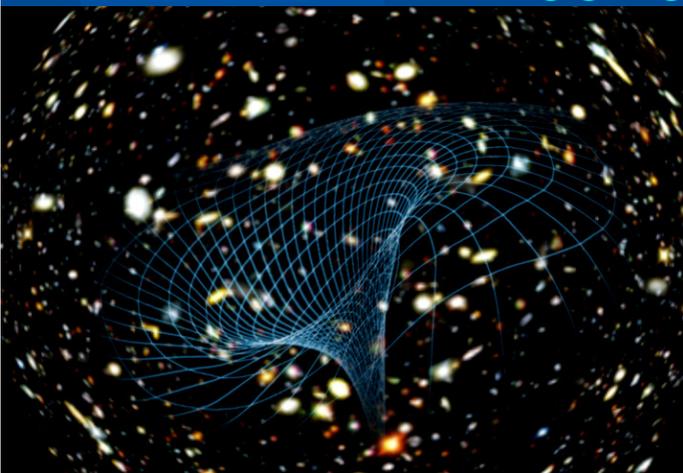


# *Can correct idea be practically useless?*

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

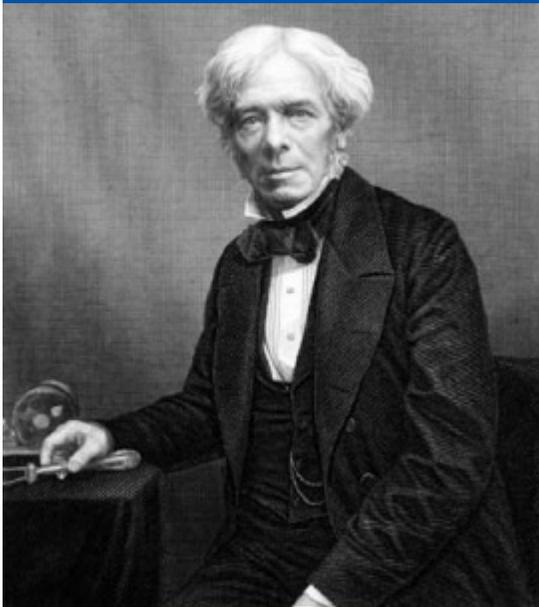
Time is slowing down by gravity



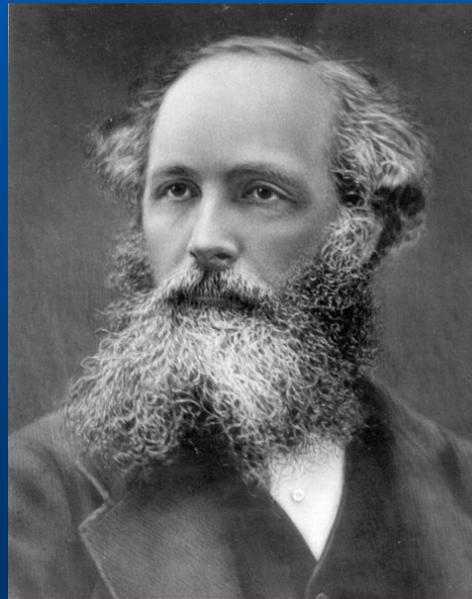
Should be taken into account in GPS!

## *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**

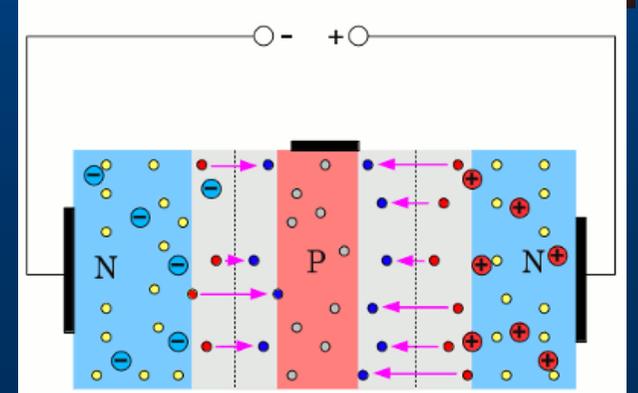
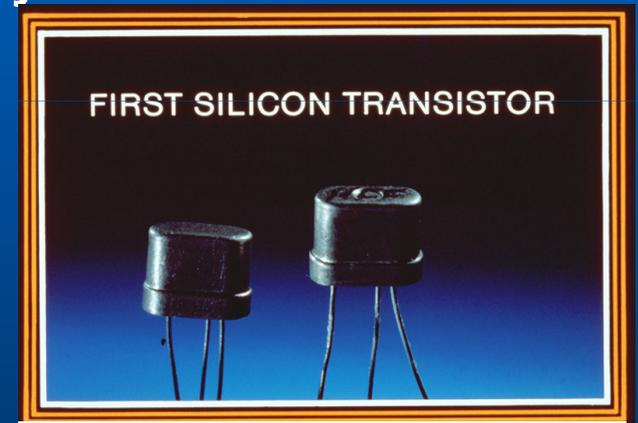
Science opens ways for dramatically new solutions



Based on classical physics

Triode (electronic vacuum tube)

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



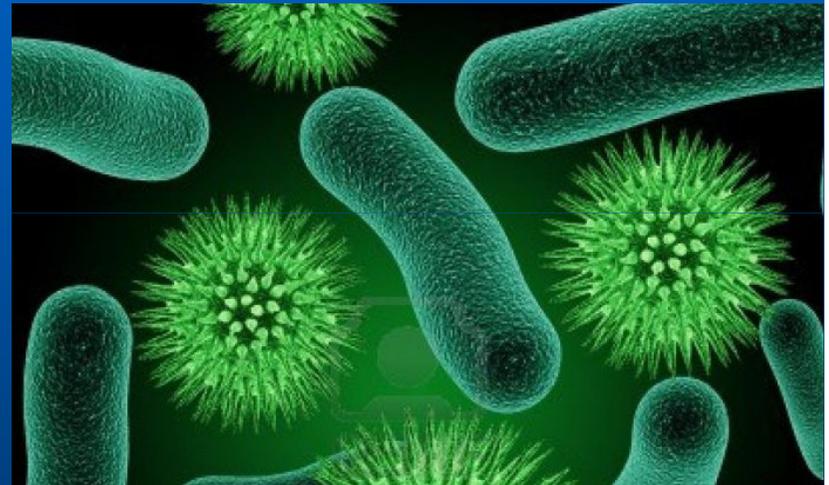
# *Science is necessary for survival of humankind*

Agriculture (“green revolution”)

Medicine (new antibiotics: arms race with bacteria)



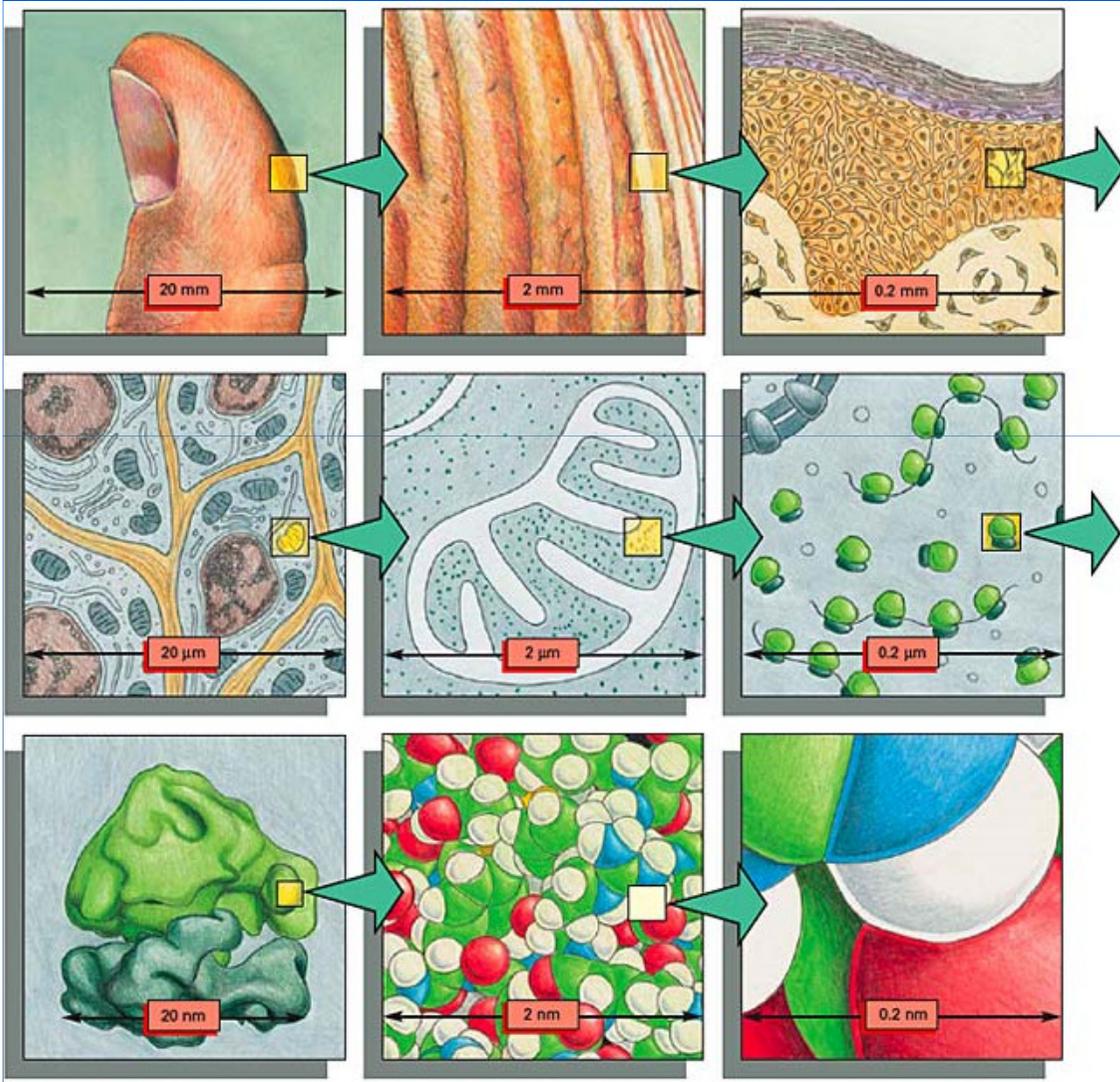
We cannot just stop: too many will die



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

Very important to know how science works

# *Structural levels of matter*

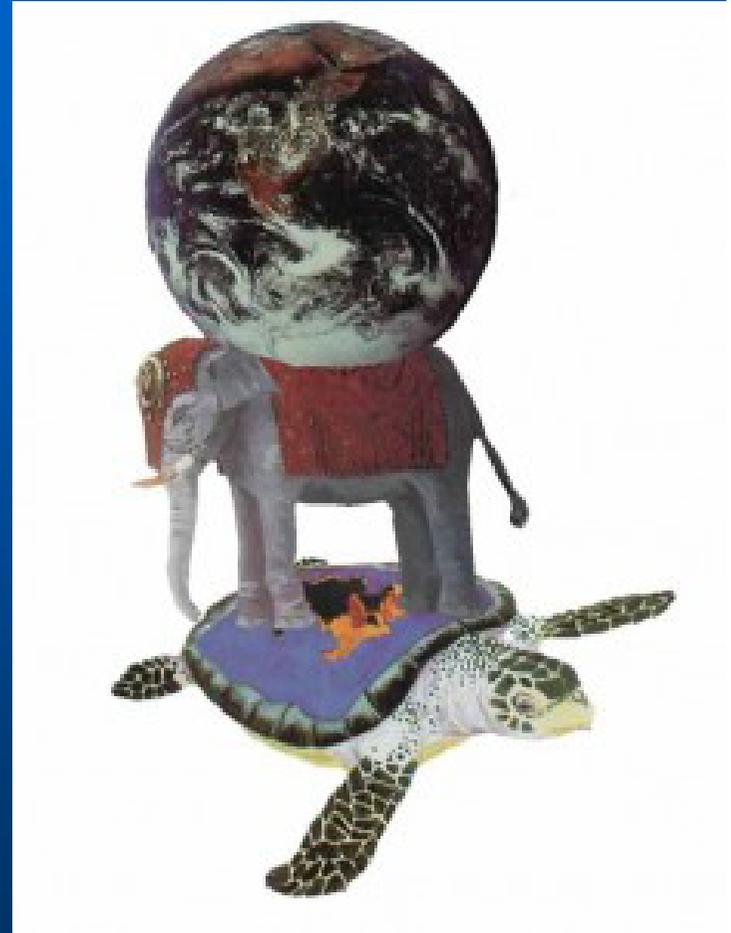


Hierarchy of levels

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

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

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

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

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

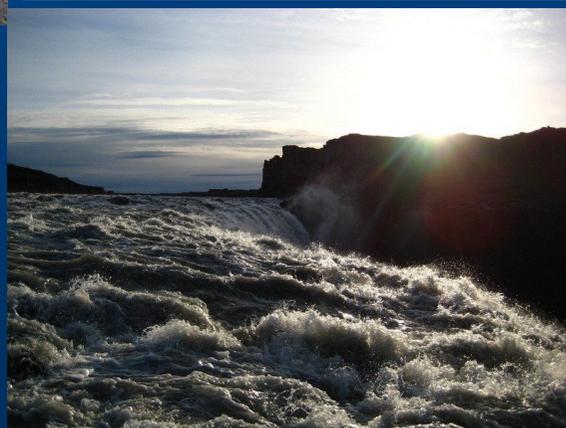
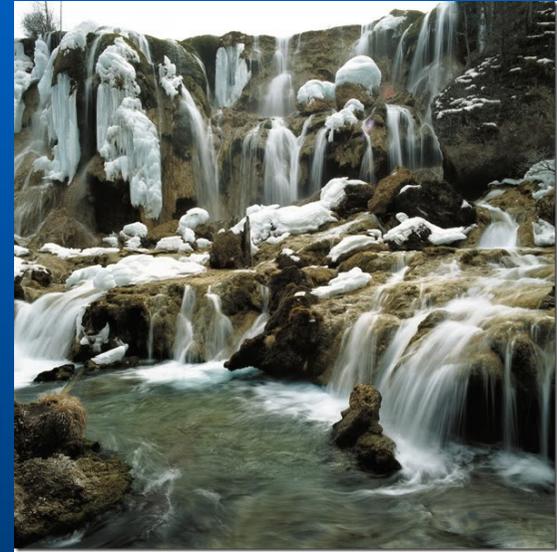
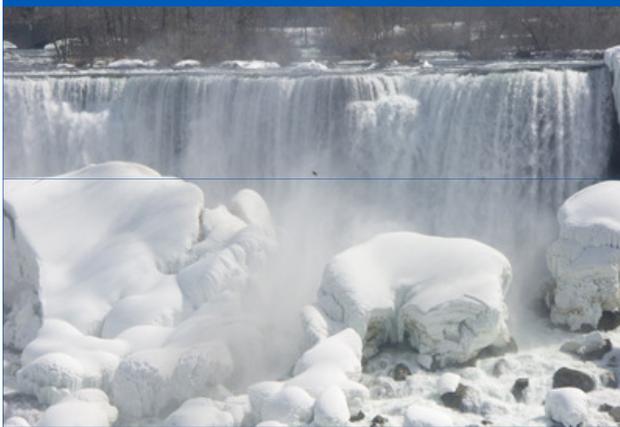
That is all. Please tell me why iridium is brittle and platinum is ductile, copper is red and silver is white, iron is ferromagnetic and vanadium is not... Not talking on biochemistry and biophysics!

# *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-Stokes 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*

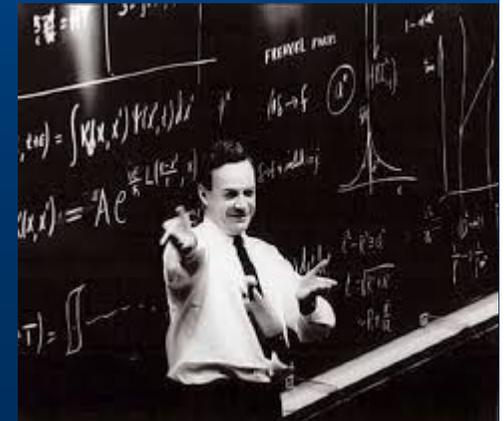
Duality of understanding and knowledge



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)**



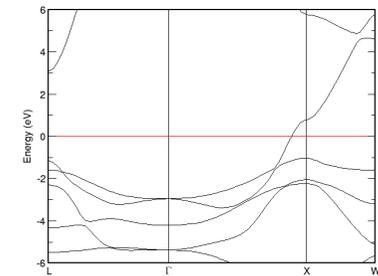
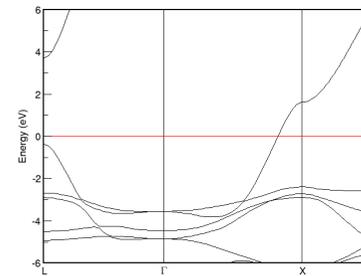
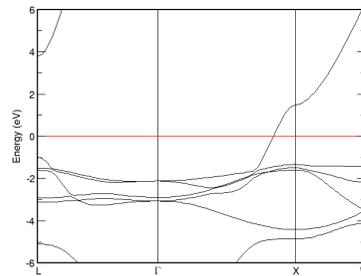
# Scylla and Charybdis



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 and gold is yellow?

Density functional calculations



Cu

Ag

Au

Can we take it as an explanation?

# Scylla and Charybdis II

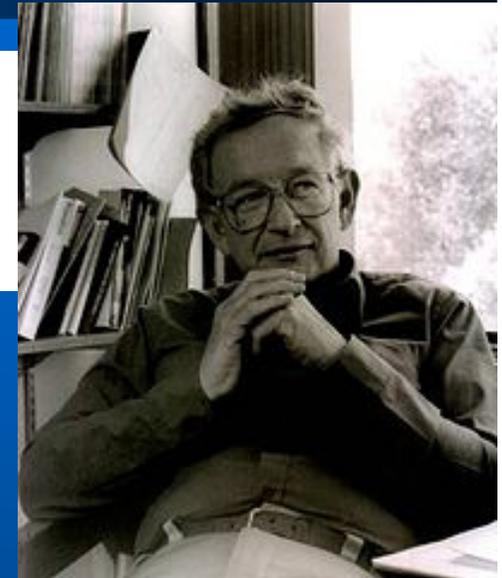


## Local moments and localized states

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 calculated 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)

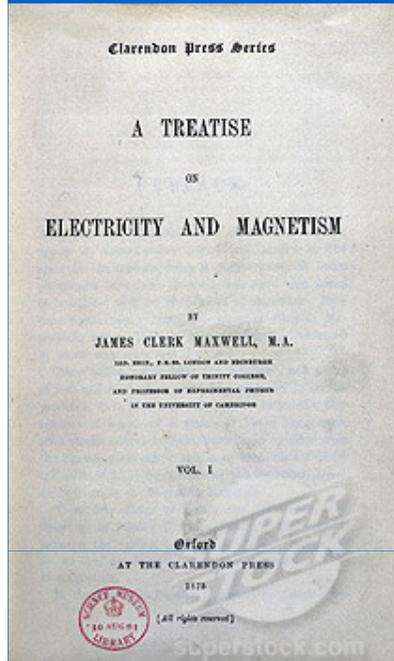
Like in a good book or a good movie: a lot of intrinsic relations, cultural references...

Analogy: a quantum computer vs classical

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

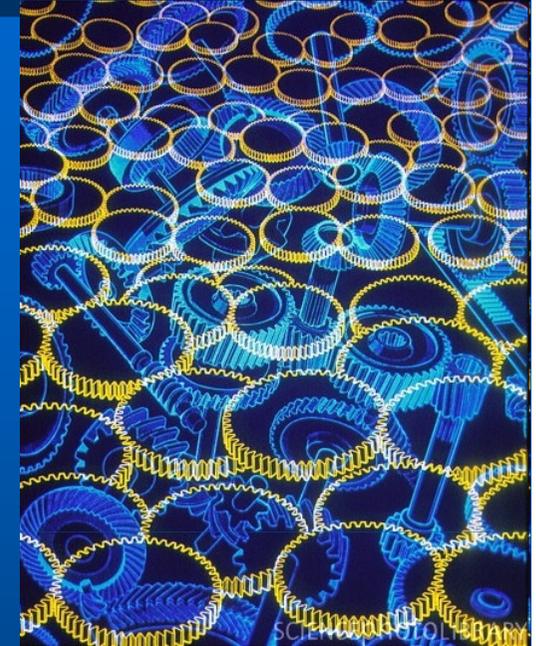
Graphene: coupling together solid state physics, soft matter, relativistic quantum mechanics and even gravity

# *Correct theories from wrong assumptions*



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 equation 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

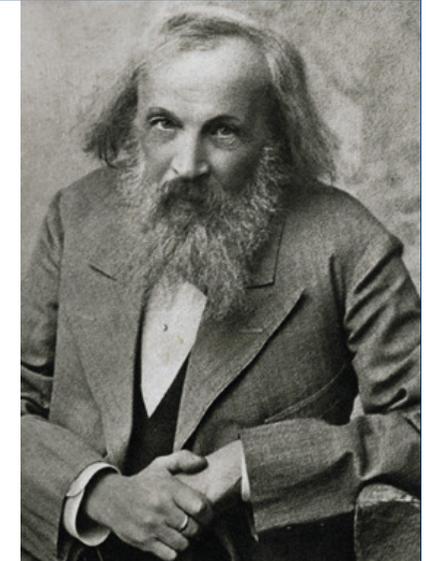
1. Klein tunneling
2. Pseudomagnetic fields due to deformations
3. Relativistic collapse at a supercritical charge

# Periodic Table

Can we understand something elementary?

**Periodic Table of the Elements**

1 1IA 11A																	18 VIIIA 8A		
1 <b>H</b> Hydrogen 1.0079			2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 <b>He</b> Helium 4.00260
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218												5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.00574	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.998403	10 <b>Ne</b> Neon 20.1797	
11 <b>Na</b> Sodium 22.989768	12 <b>Mg</b> Magnesium 24.305		3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8		9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 <b>Al</b> Aluminum 26.981539	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.4527	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.95591	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.732	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92159	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80		
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.9072	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.9055	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.29		
55 <b>Cs</b> Cesium 132.90543	56 <b>Ba</b> Barium 137.327	57-71 Lanthanide Series		72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.9479	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.9665	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98037	84 <b>Po</b> Polonium [208.9824]	85 <b>At</b> Astatine 209.9871	86 <b>Rn</b> Radon 222.0176	
87 <b>Fr</b> Francium 223.0197	88 <b>Ra</b> Radium 226.0254	89-103 Actinide Series		104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [289]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Uuq</b> Ununquadium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Uuh</b> Ununhexium [288]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown	
				57 <b>La</b> Lanthanum 138.9055	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.9127	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.9655	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92534	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967	
				89 <b>Ac</b> Actinium 227.0278	90 <b>Th</b> Thorium 232.0381	91 <b>Pa</b> Protactinium 231.03888	92 <b>U</b> Uranium 238.0289	93 <b>Np</b> Neptunium 237.0482	94 <b>Pu</b> Plutonium 244.0642	95 <b>Am</b> Americium 243.0614	96 <b>Cm</b> Curium 247.0703	97 <b>Bk</b> Berkelium 247.0703	98 <b>Cf</b> Californium 251.0796	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.0951	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.1009	103 <b>Lr</b> Lawrencium [262]	
				Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides						



D. I. Mendeleev

# Carbon, element #6

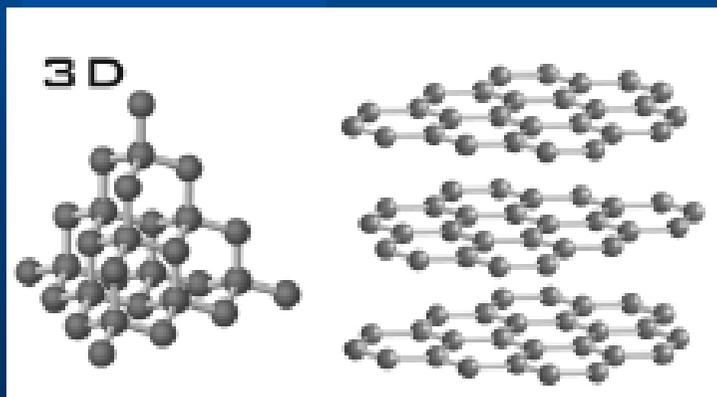


Diamond

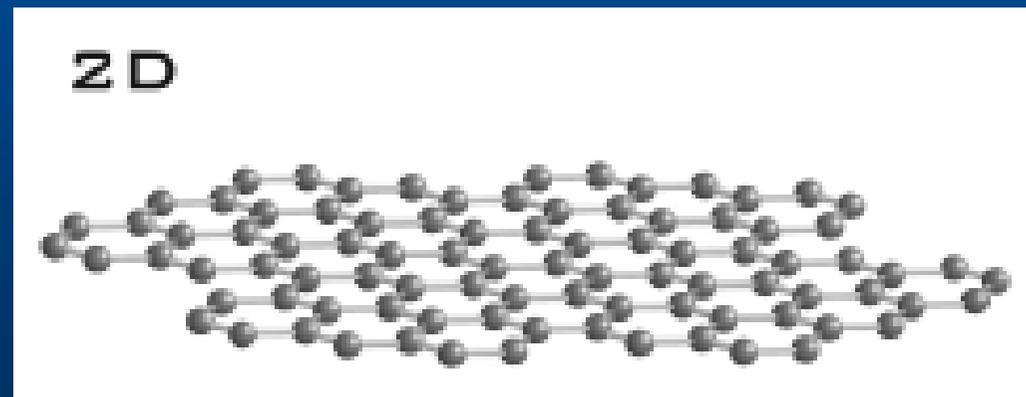


Graphite

Determined by arrangement of carbon atoms

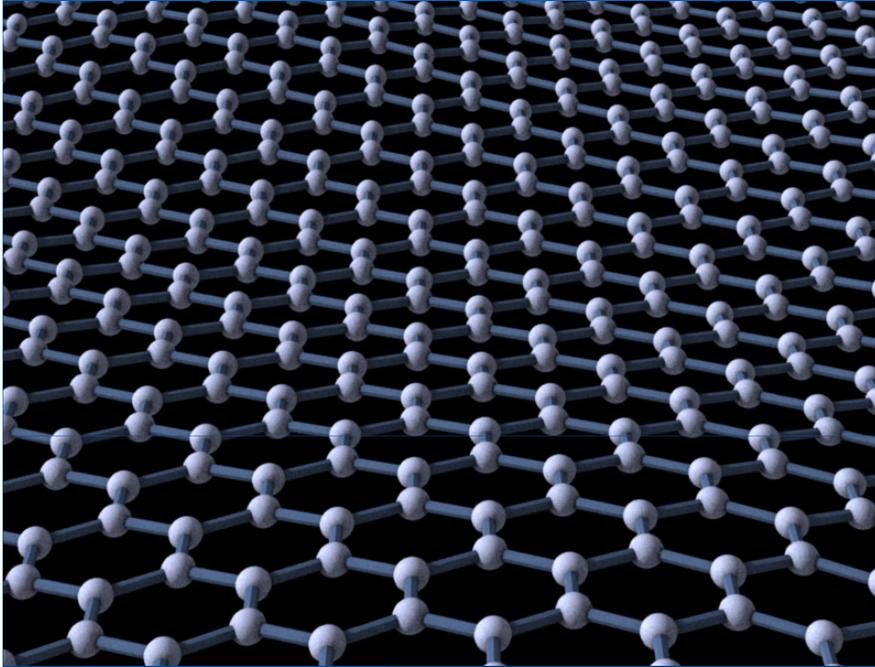


Diamond, Graphite



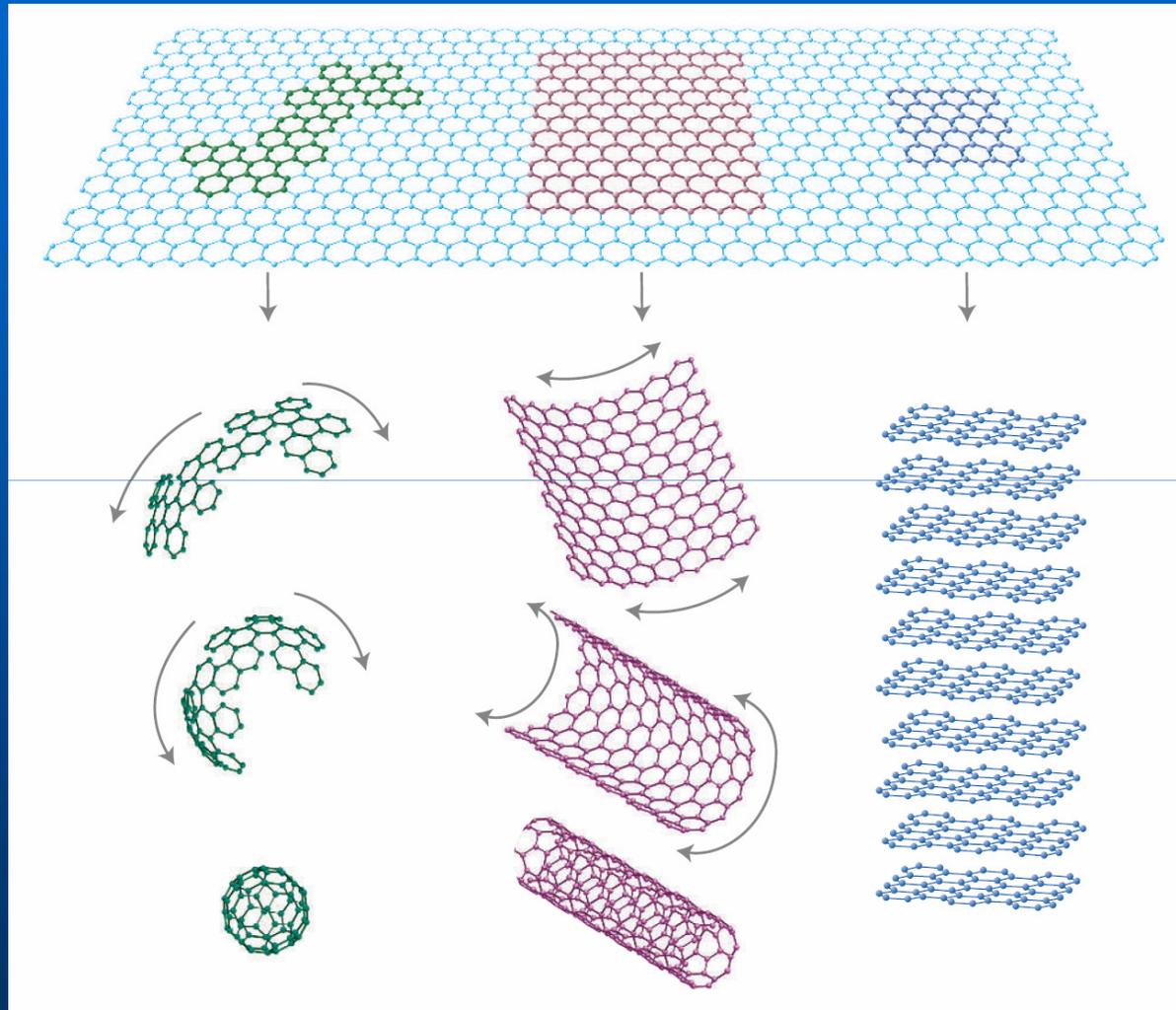
Graphene: a prototype 2D crystal

# *Honeycomb*



Hexagonal crystal lattice

# *Mother of all graphitic forms*



Fullerenes Nanotubes Graphite

# Discovery of graphene

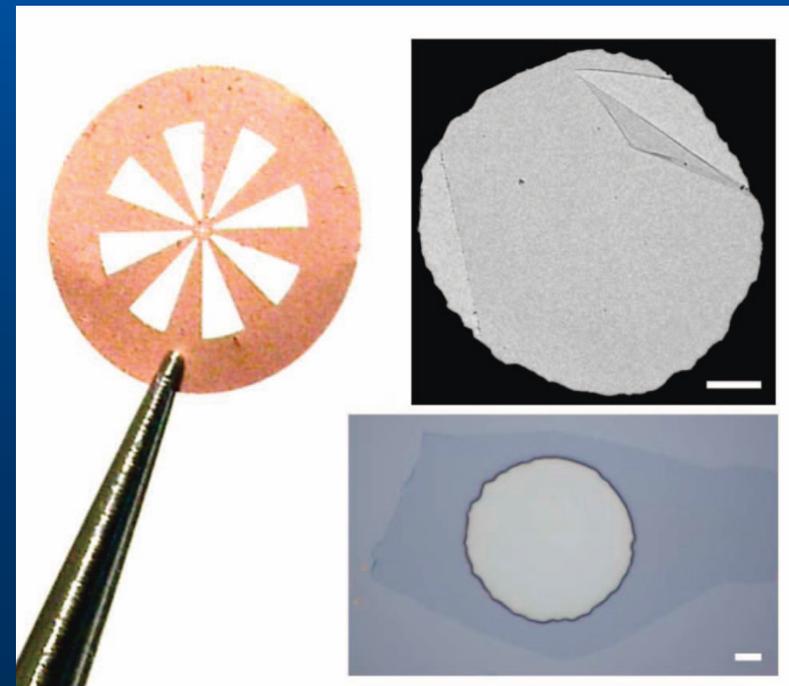
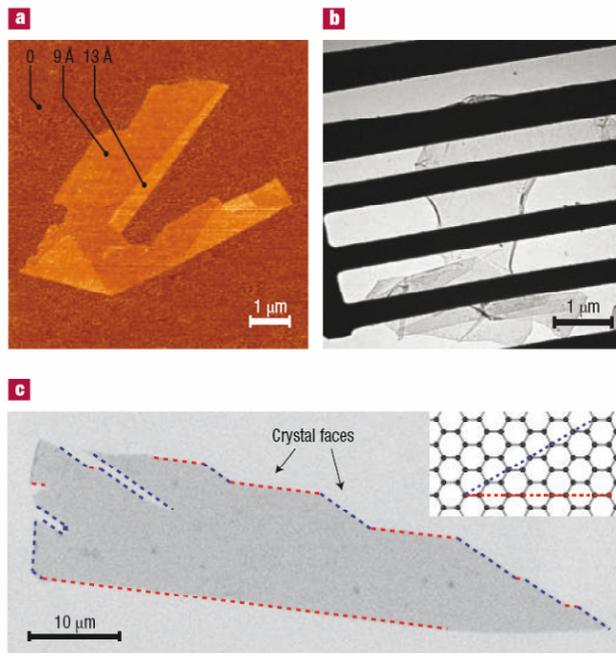


## Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,<sup>1</sup> A. K. Geim,<sup>1\*</sup> S. V. Morozov,<sup>2</sup> D. Jiang,<sup>1</sup>  
Y. Zhang,<sup>1</sup> S. V. Dubonos,<sup>2</sup> I. V. Grigorieva,<sup>1</sup> A. A. Firsov<sup>2</sup>

22 OCTOBER 2004 VOL 306 SCIENCE

Andre Geim and Kostya Novoselov  
Nobel Prize 2010

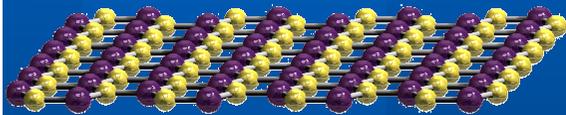
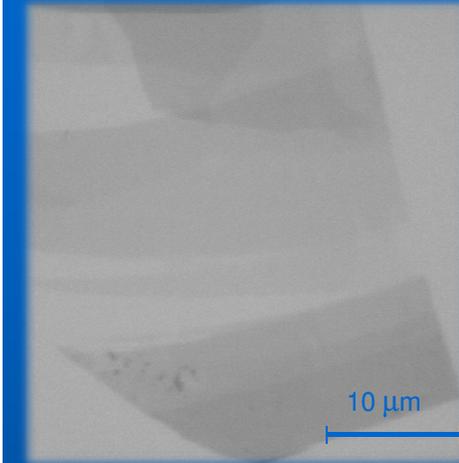
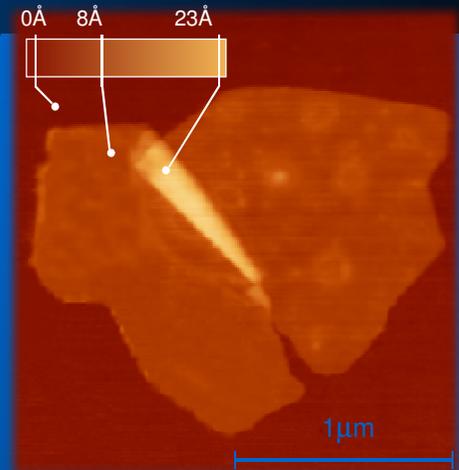


# Beyond Graphene

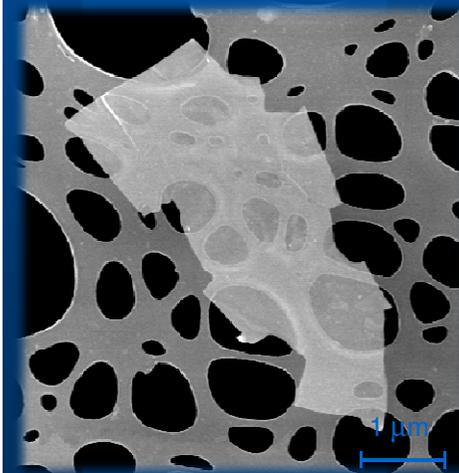
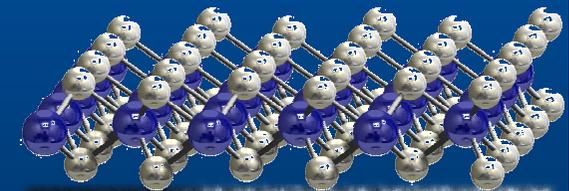
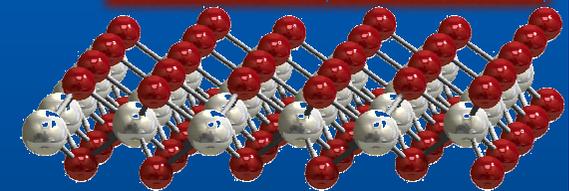
2D boron nitride in optics

2D NbSe<sub>2</sub> in AFM

2D crystals from other layered materials

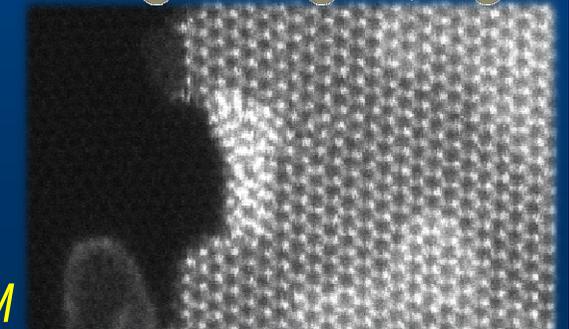


Novoselov et al  
PNAS (2005)



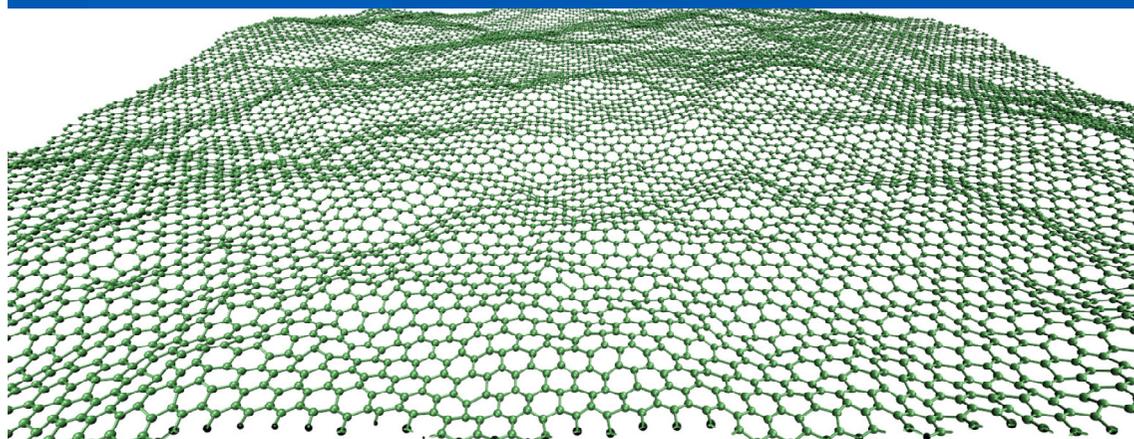
2D Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub> in SEM

2D MoS<sub>2</sub> in TEM



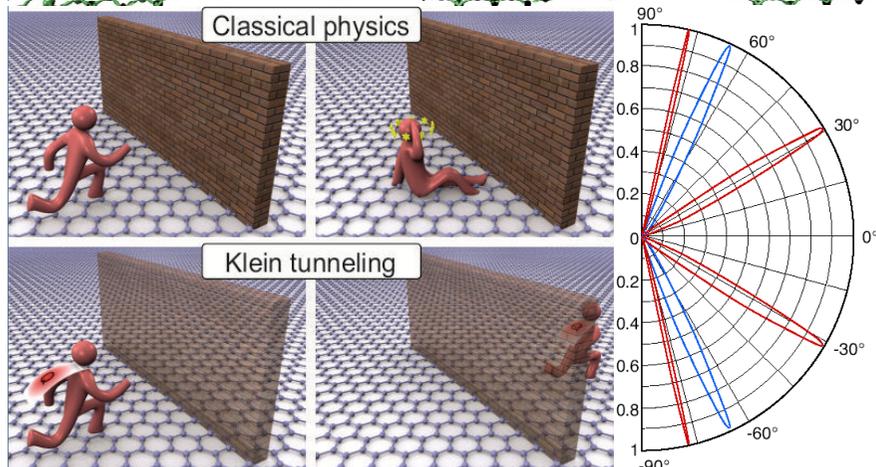
# Why graphene is interesting?

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?

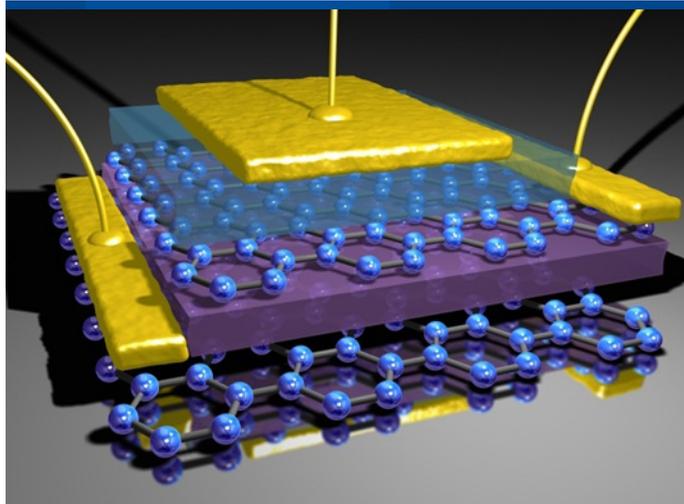
Conventional transistor: Cannot be locked due to Klein tunneling

Solution: a “vertical geometry”

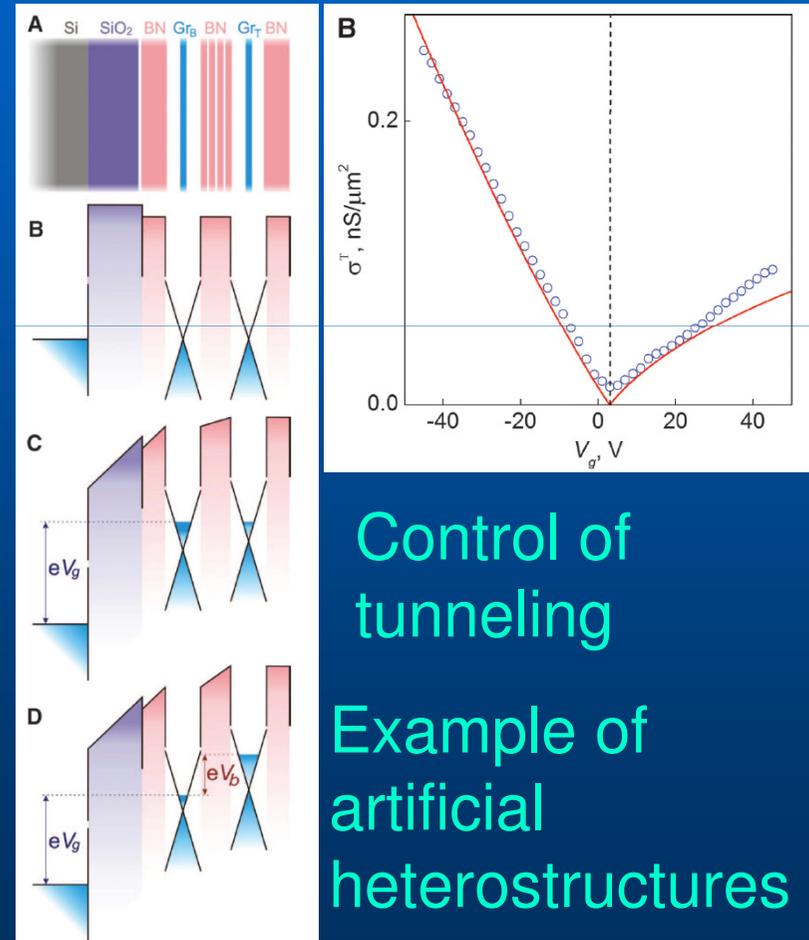
## Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures

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

SCIENCE VOL 335 24 FEBRUARY 2012



Graphene  
Spacer  
Graphene



Control of  
tunneling

Example of  
artificial  
heterostructures

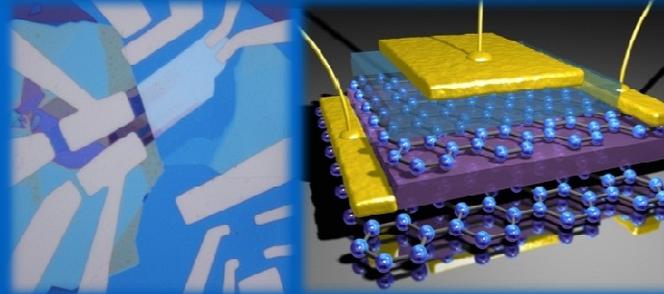
# Heterostructures Based on 2D Crystals

## Tunnelling Transistor

Manchester Science '12

Manchester Nature Nanotechnology '13

$on/off > 10^6$   
suitable for modern  
electronics



## Solar cells

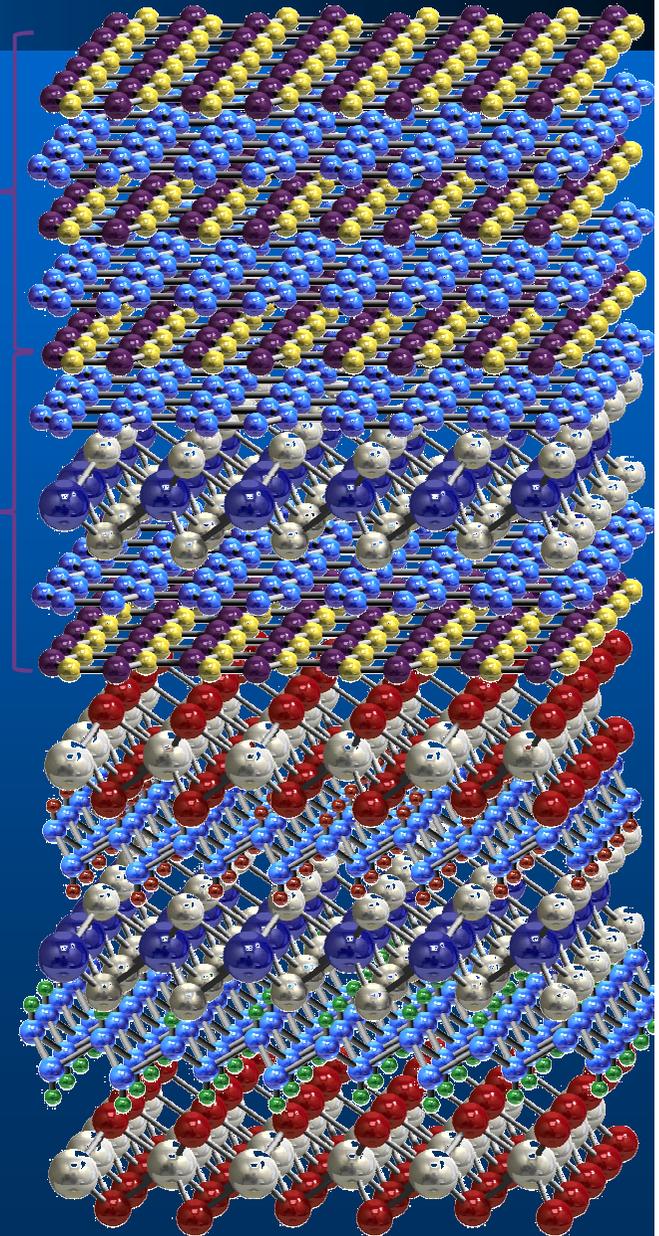
Manchester Science '13

large quantum efficiency

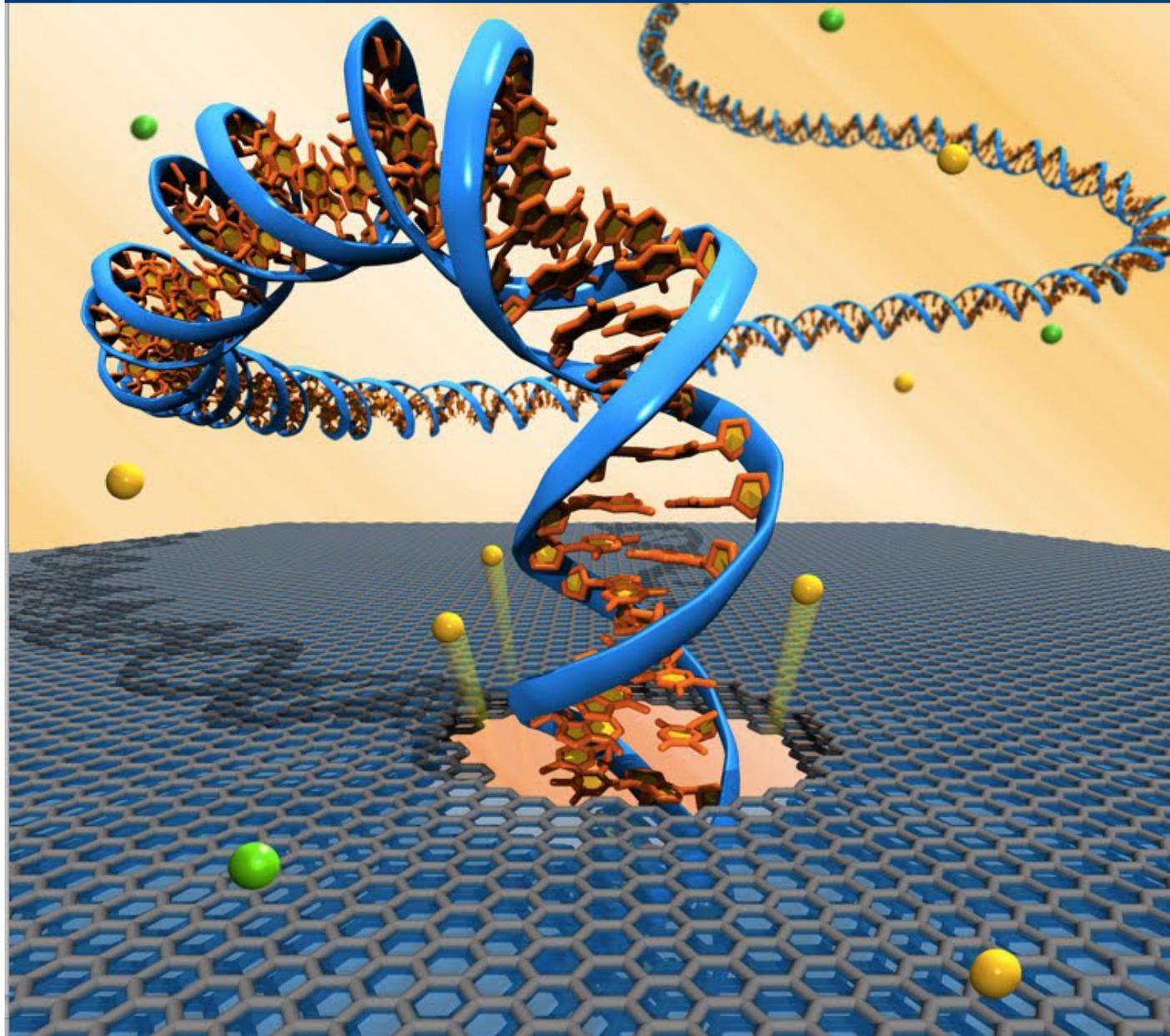


Large number of 2D crystals –  
infinite functionality  
Many different devices possible

Layer-by-Layer Material Engineering



# *Unexpected applications (e.g., biology)*

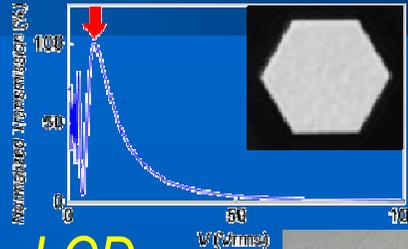
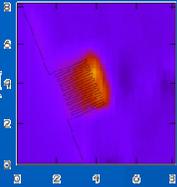
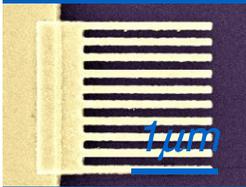


## DNA sequencing

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

# All Major Applications are Realistic

Photovoltaics  
Photodetectors



Solar Cells

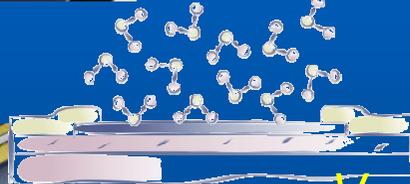
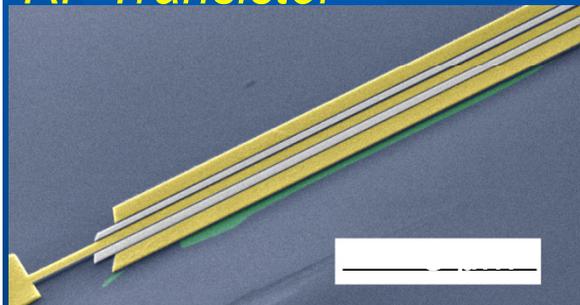


Tactile Display

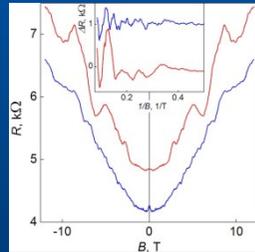


Touch-screens

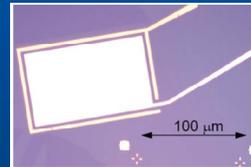
Electronics  
RF Transistor



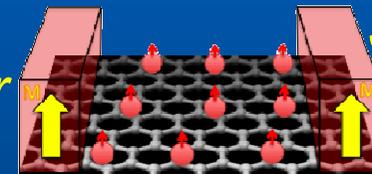
Gas Sensor



Variable Capacitor



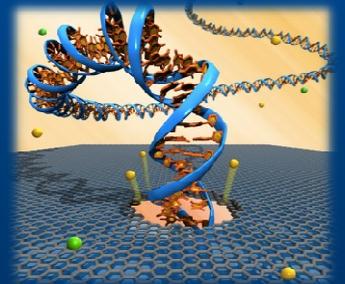
Strain Gauge



Spin Valve

Healthcare and Bio

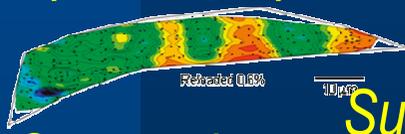
DNA Sequencing



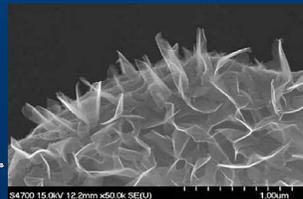
Composite Materials

Mechanically Strong;  
Conductive; Optically Active

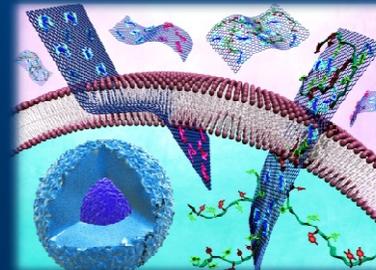
Graphene Paper



Composites



Supercapacitors



Drug delivery

Sensor

