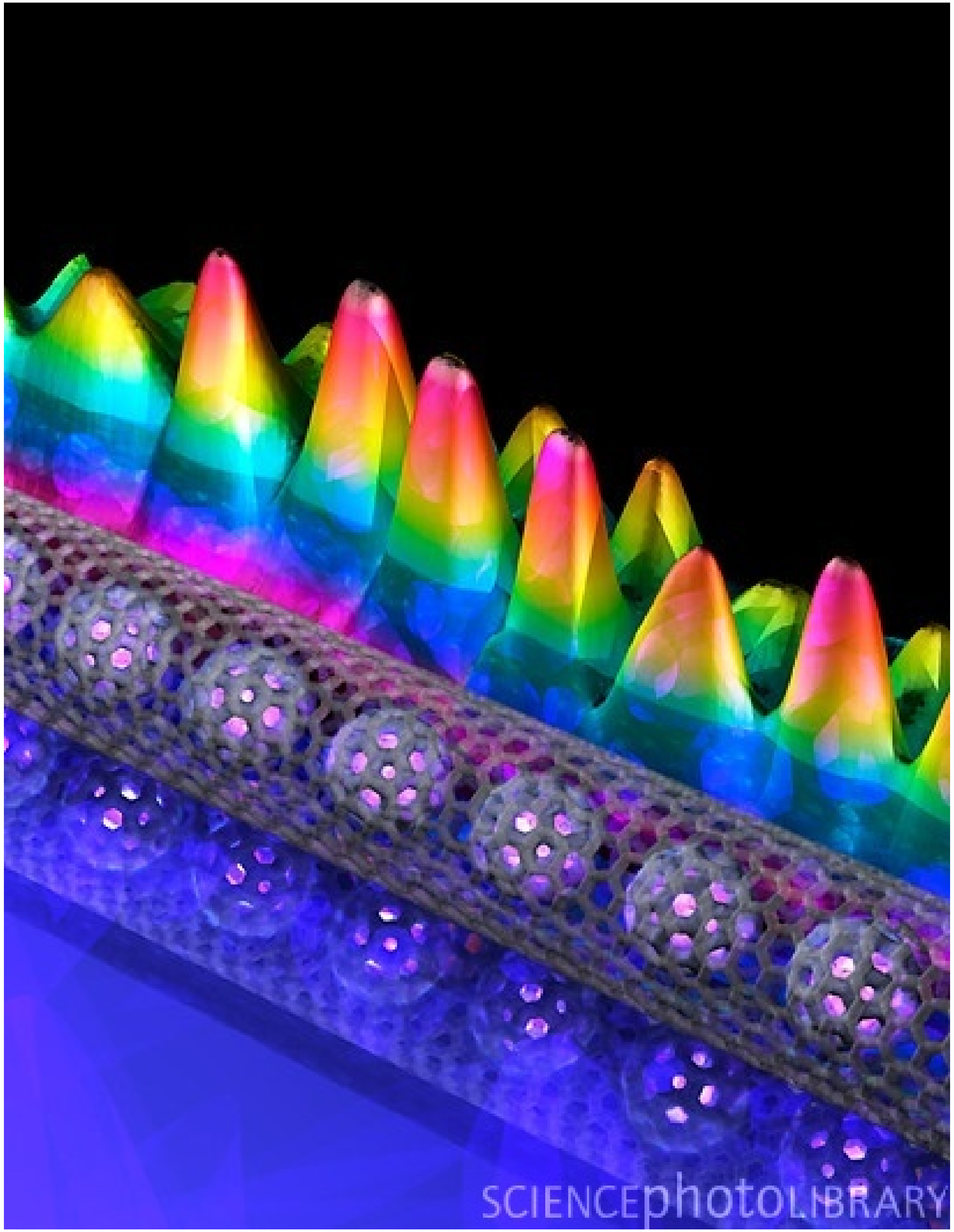

VERY Informal introduction to

Computer modelling of *Carbon* Nanotechnology

CPD 2012

Manuel Melle Franco
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University of Minho

who am I?

- **Researcher in the HPC group of DI UMinho**
- CV: Natural scientist:
  - Ph.D. Physics
  - M.Sc. Materials Science
  - First Degree in Physical Chemistry
  - Large experience in scientific computing:
    - **Research: computer models for NANOTECHNOLOGY**

I am here for you so PLEASE <u>DO INTERRUPT ME</u> AT ANY TIME!!!

Introducion

- I could speak hours about very technical an obscure stuff **(this guy rules!)** that would be very difficult to follow and you would not get much out of it
- I will try show you something, useful from my point of view (a physicysts working with computer scientist).
- IT might BE TOO MUCH INFORMATION SO INTERRUPT ME WHEN YOU HAVE QUESTIONS!

Experiment and Theory

Mathematical models

Experiment vs. theory

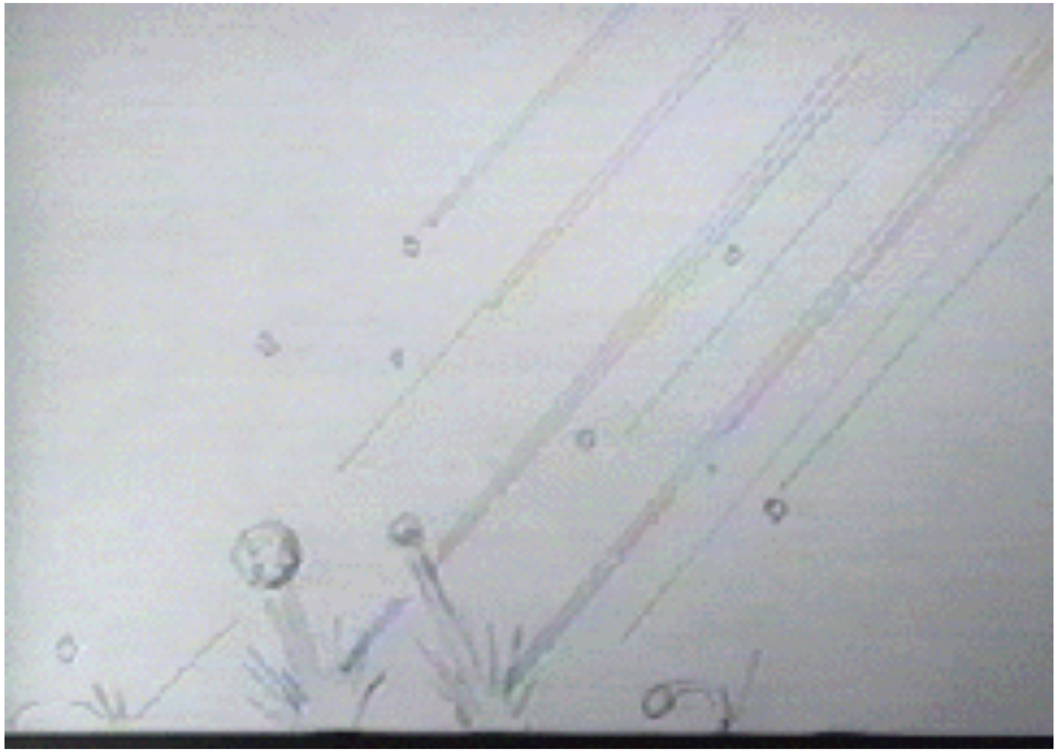
- Experiment: WHAT WE OBSERVE

- Theory: HOW WE EXPLAIN/RATIONALIZE WHAT WE OBSERVE

Example: Galileo's Experiment

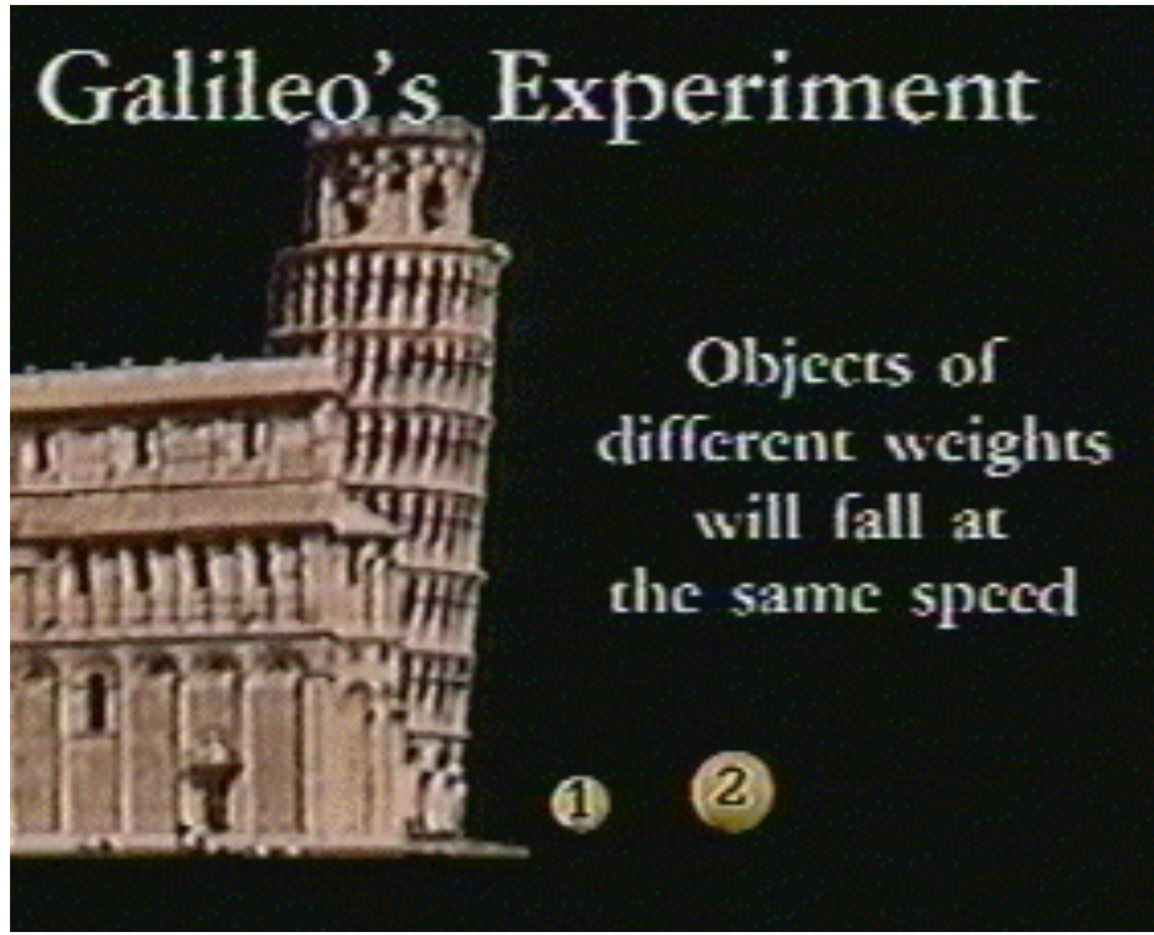
- Aristotle's theory: heavier objects fall faster

- Galileo in a hail storm: all hail sizes touch the ground at the same time, NO PREFERENCE with size or weight
- Galileo found a way to find how this thing really worked! (designed an EXPERIMENT!)



Galileo's experiment (17th century)

- Made **experiment** that found Aristotle was wrong (A. did not check, HE ASSUMED, *we do the same most of the time*!!!!)
- Proposed a simple MATHEMATICAL model that could reproduce his experimental data and **predict** what would happen in other



Why theory?

- UNDERSTANDING
- Cause-effect relationship
- why natural phenomena happen!!!!!!

David Hume, philosopher 18th century: **water boils when heated, but can we be 100% sure that it will boil NEXT time???? Yes or no?**

Now that we know 100 % why water boils and what that physically means, we are 100% sure it will boil ALL TIMES, because we know the process completely, **SCIENCE says IT MUST boil and so it will!!!**

Why model something?

Mathematical model:

- Reproduction
- Extrapolation to exp. unknown cases/conditions
- Prediction

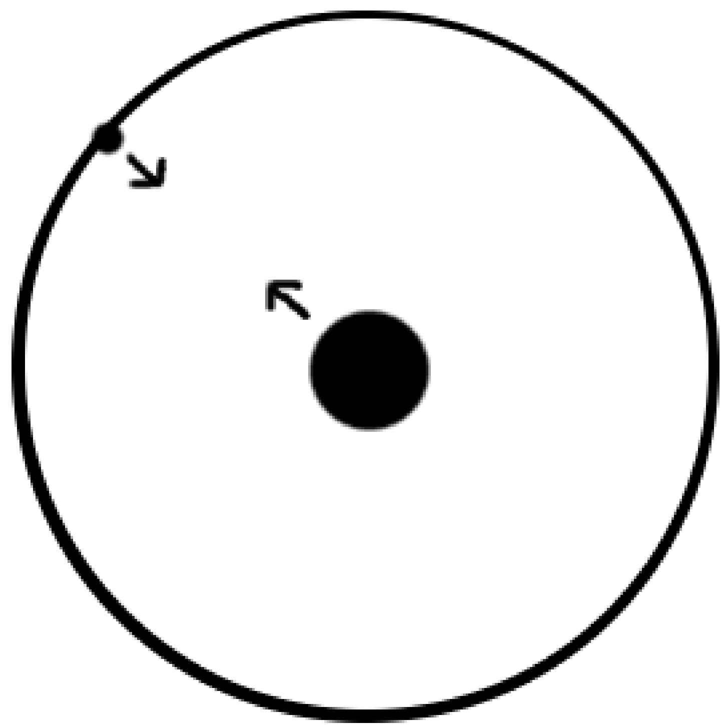
Nature follows easy rules (not obvious ones), but too many different interacting objects so nature is complex!

Theory/modelling is fundamental for advanced technological use of nature! example: semiconductor industry, etc

Mathematical models: The two-body problem

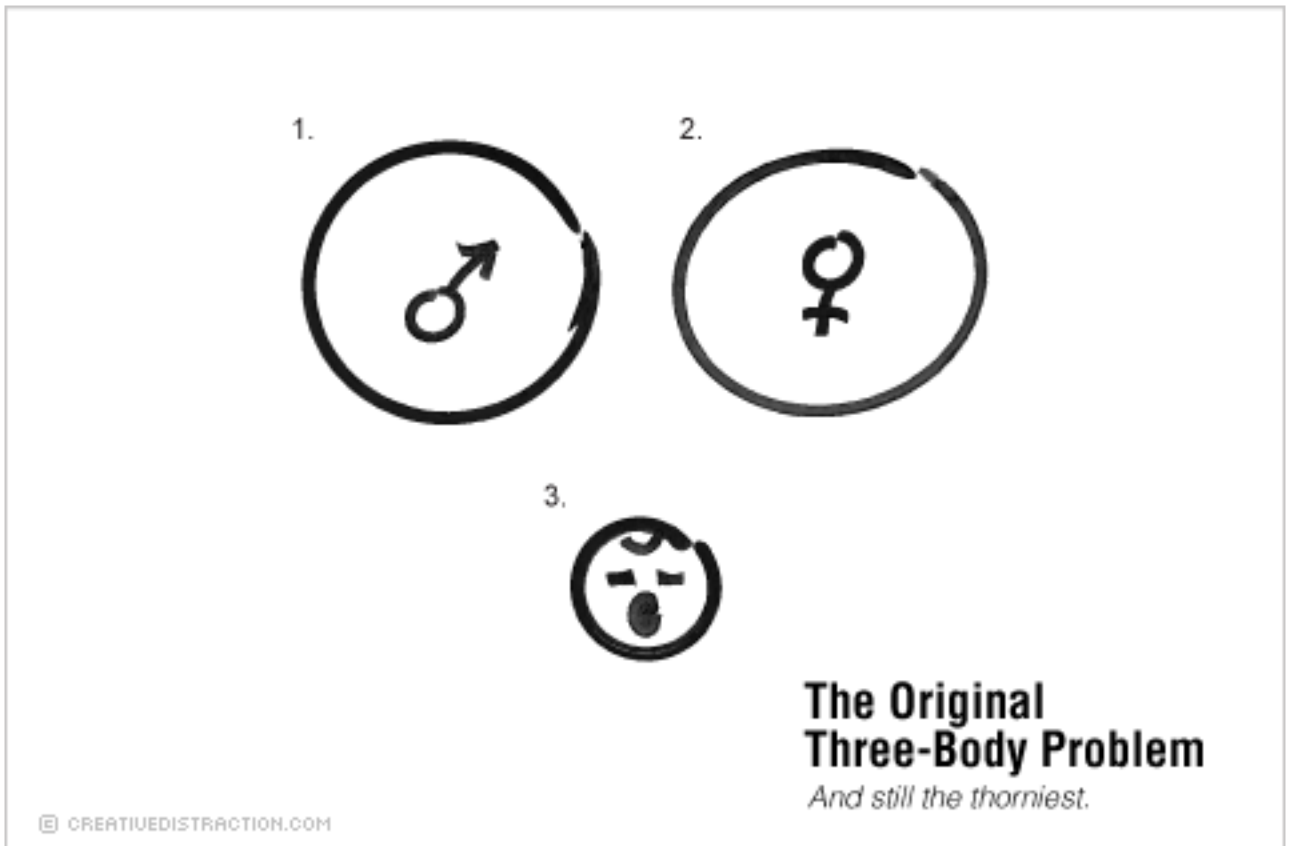
The **two-body problem (nothing to do with sex!)**:
motion of two bodies that interact with each other. Examples:

1. Moon and the earth
2. Electron "orbiting" hydrogen nucleus



The "original" Three body problem

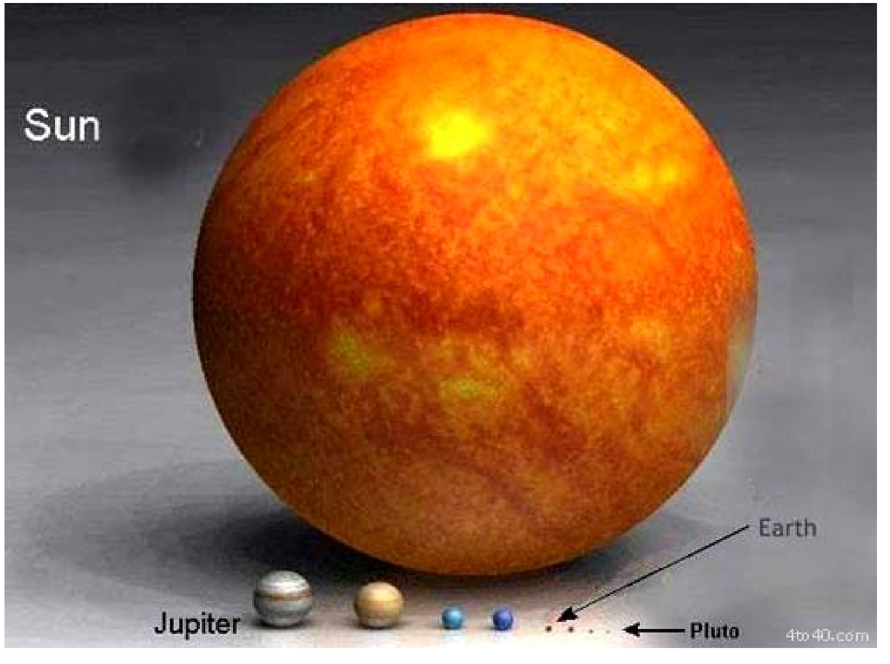
Mother + Father + child = No exact solution!!!



Mathematical models: The two-body problem

The Two-body problem can be solved analytically (i.e **EXACTLY**).

By contrast, larger (>= 3 interecting bodies) bodies cannot be solved exactly, except in special cases and have to be solved **NUMERICALLY** (approximatedly). Ex: Planet orbits:



Numerical vs. Analytical models

Numerical

1. Approximated (for real numbers)
2. Relative Accuracy, typically it depends on number of iterations
3. Easy but very repetitive, only most simple cases are doable by hand (in a reasonable time) **ideal for COMPUTERS**

Analytical

1. Exact
2. Always 100 % accurate
3. Difficult (creative tought)
4. Its working can give insight in the problem at hand: **fundations of Quantum Mechanics was ALL done with pen and paper**

Computer simulation = automatidc numerical procedure

- First Simulation (state of the art, 1945):
  - It was a simulation of **12** **hard spheres** (BODIES) to model the process of nuclear detonation during the Manhattan Project in World War II
- State of the art (2005): motion of **a 2.64-million-atom model of a** **ribosome** on 768 parallel processors (Ribosome is a protein made molecular machine that builds proteins from genetic code! **Nature's Nanotechnology**)

Atomistic modelling in natural sciences!

why is High Performance
Computing is needed?

Computational, natural, science

- Exponential growth in commodity PC's power:
    - experimental science more EXPENSIVE than ever
    - virtual science is, in comparison, cheaper than ever

RESEARCH in virtual theoretical science is very complex, need **highly qualified, highly trained, Ph.Ds level researchers!**

- **User-friendly software slowly appearing**
- **Large high quality HOW-TO needed: computer model of nature can be tricky!**

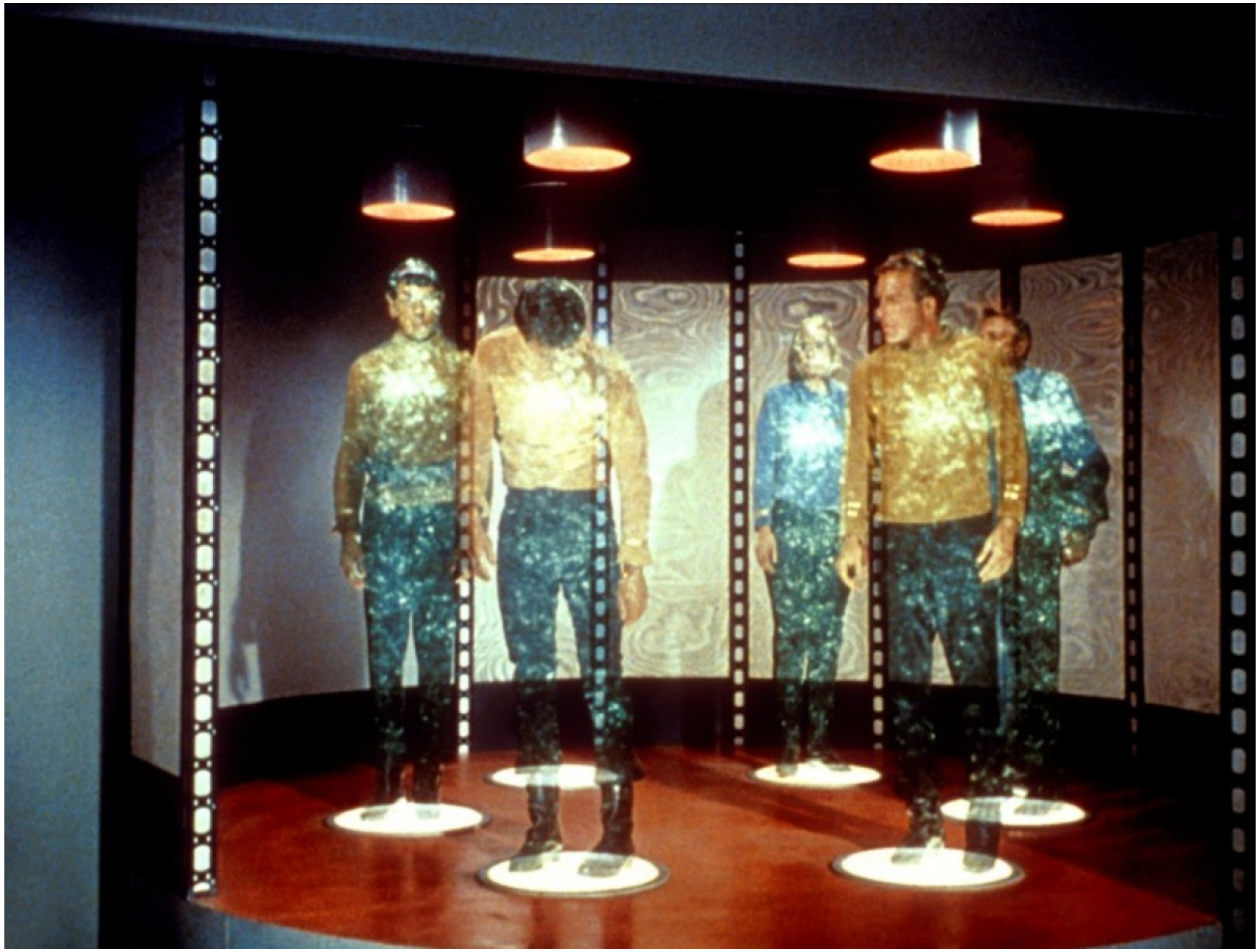
Computational, natural, science

- Current state, amazing powerful PCs!
    - **TODAY**: This **laptop**: i5 M460 @2.53GHz = 2x4x2.53 = **20 gigaFLOPS** (theoretical)
    - **15 years ago**: One of the 500 fastest, **parallel, computers of the world!** (www.top500.org)
    - The first system to achieve **1 petaFLOPS [peta=10**15] (2007):** distributed home computers using PS3 and PCs (GPUS) **folding@home** [folding proteins!]

I started doing this in **1996**, **1st generation pentium PC with first linux distribution in FLOPPIES!**

"Beam me up Scotty!"

Molecular Models: a way to "digitalize" matter, yet not like **Star Trek telettransport**!



Persons or non-living items would be placed on the transporter pad and are dismantled particle by particle by a beam with their **atoms being patterned in a computer buffer** and converted into a beam that is directed toward the destination, and then reassembled back into their original form (usually with no mistakes).

Digitalizing the world with atomic resolution (SIZE!)

- 1 gram of carbon has ~5 x 10^{22} atoms
- Store atomic positions of **1 gr carbon** atoms in single precision (4 byte):
  - 6 x 10**23 bytes = (SI) 0.6 **yottabytes**
  - **6 hundred thousand millions of TB harddrives**
  - piling up laptop HDs (1km HDs= 100000 TB):
    - 1 yottabyte = 10**12 HDs=**10 million kms of HDs** (diameter of the earth is ~ 12000 km

- Classic **Star Trek** may have weird dresses but also **amazing storage density than us**!

Digitalizing the real world with atomic resolution (SIZE!)

Models Impossible? NO!

- **Most properties of crystals of carbon (graphite/diamond) can be described just by 2 atoms models**

- Most information in 1 gr of carbon is extremely redundant:
  - 1 gr carbon = 5×10^{22} atoms (BORING!!!)
  - 1 human brain = 9×10^{10} cells (**exciting!**)*.

*:http://www.guardian.co.uk/science/blog/2012/feb/28/how-many-neurons-human-brain

Digitalizing the real world with atomic resolution (TIME!)

- Our body is mostly built by light atom molecules (H, C, O, N)
- Time in numerical models is discrete
- Atoms, being very small and very light move very fast:
  - require timescales ~ 1 fs (10^{-15} seconds).
  - Discretize time in chunks of 1 fs!

Digitalizing the real world with atomic resolution (TIME!)

Different important molecular processes happen in different time scales:

- **Miliseconds**, like protein folding, are now reached with supercomputers for small, few atoms, systems **(10^{12} iterations,** 1 tera-iterations**)**.
- 1 second, peta-iterations, doable with a dedicated petaFLOP computer!

NOTICE that it is not enough simulating a second, IT HAS TO BE a second where something very interesting HAPPENS.

Digitalizing the real world , why HPC computers? SUMMARY

- Many iterations:
  - Larger scales:
    - Size: Simulations of millions of atoms
    - Time: ms simulations
    - Size & time
  - Very complex methods:
    - Quantum mechanical methods (simulation with explicit electrons can be severals orders of magnitude heavier)

Computing natural sciences

Natural Scientists vs. computer scientists!

Computational vs computer scientists?

Computer scientists (ex):

- Formal education programming (C, C++, etc)
- Profilers, debuggers, ...
- (**Should**) understand processor architecture
- Should be able to admin a unix/linux machine!

Natural scientists (ex):

- Some, cheap, self-taught programming (matlab, fortran, python, ...)
- what?
- WHAT????
- most computational natural scientists do

Natural vs computer scientists?

Natural scientists (ex):

- (Should) know GOOD physics/chemistry/biology
- really know why algorithms have to do that in scientific software3
- Know what is the main purpose of simulations: **WHY!!!**

Computer scientists (ex):

- WHAT??????
- what????
- what??????

Starting working in a new field, there is always more than you don't know than what you do know!!!!!

is formal training needed?

- In 2003, I designed, bought and set up a **30K euros PC cluster**.
- It run flawlessly till 2009 (with a maximum, rare downtimes of one hour).
- **I never formally studied computing!**

Everybody can try to learn and do ANYTHING:
It takes time, effort, a large amount of frustration, and stubbornnes!

In other words...

If you really want to do something, there is nothing, intrinsic, to stop you!

Natural scientists are not born like that (it is not a genetic trait) neither are computer scientists, we BOTH have LEARNT to do so!

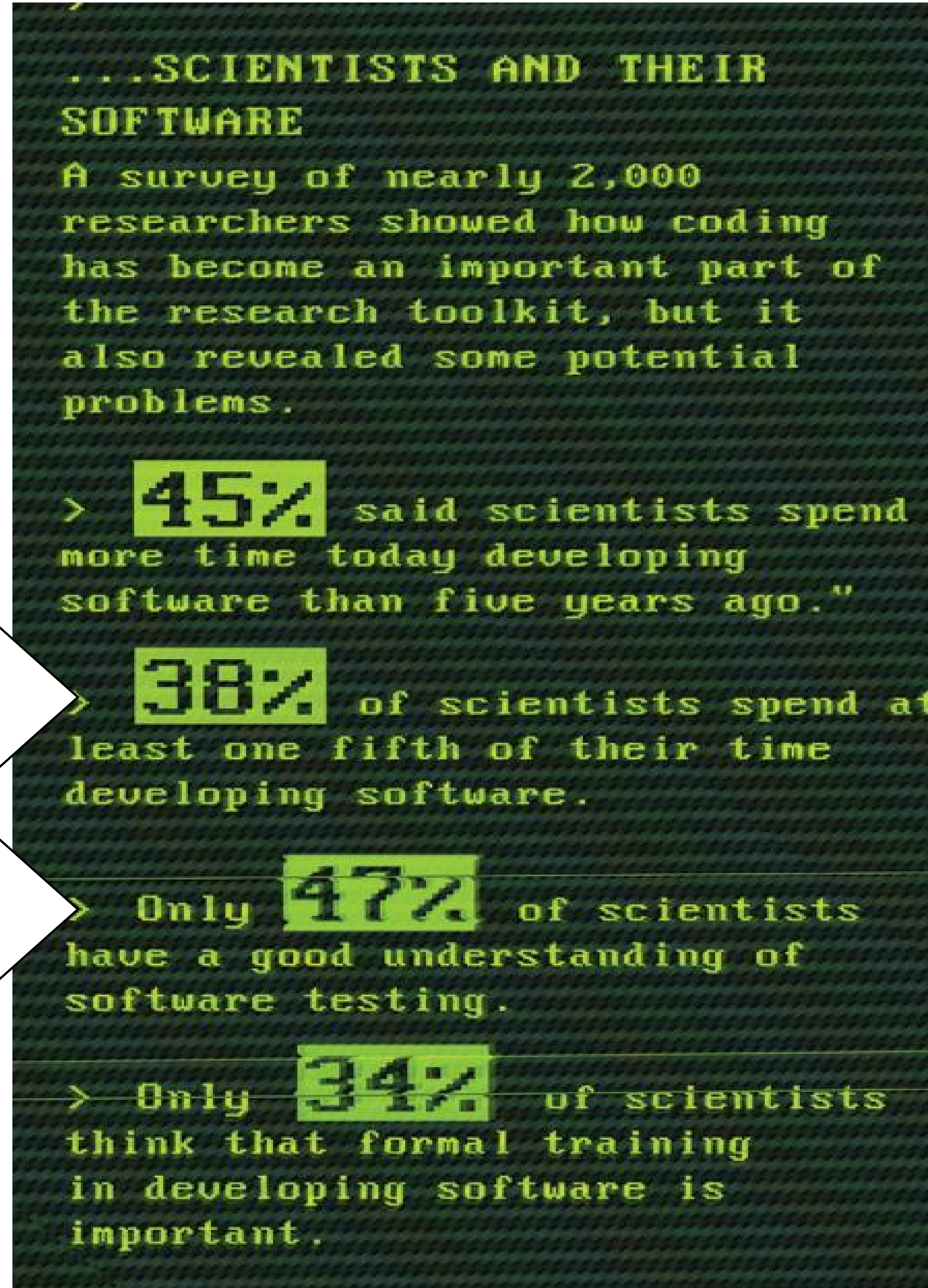
Most scientific codes are written developed and extended by

Natural scientists

Is this good?????

Computational science: ...Error …why scientific programming does not compute. Zeeya Merali

Published online 13 October 2010 | **Nature** 467, 775-777 (2010) | doi:10.1038/467775a News Feature



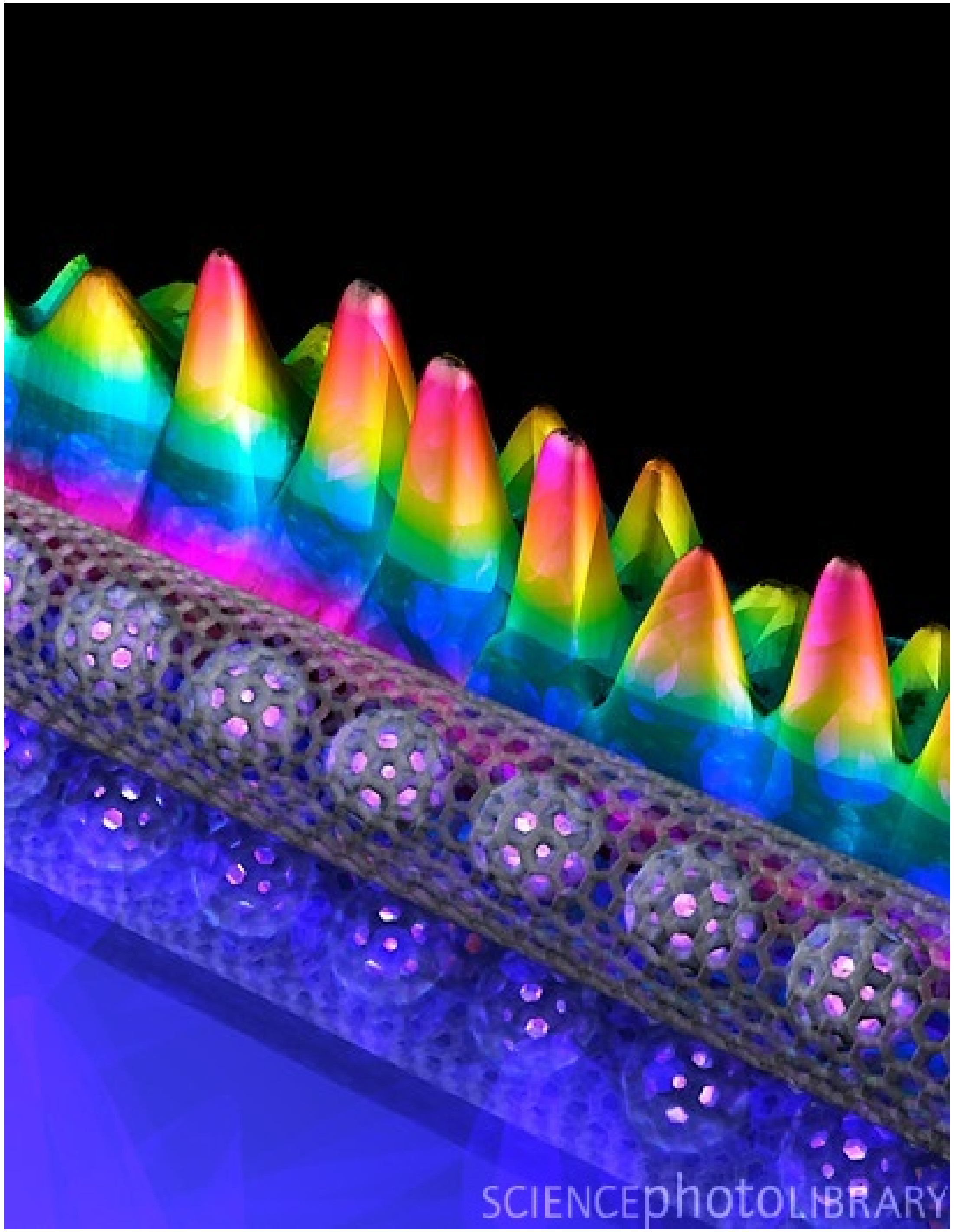
Publish your computer code: it is good enough Nick Barnes

Published online 13 October 2010 | **Nature** 467, 753 (2010) | doi:10.1038/467753a

I am a professional software engineer and I want to share a trade secret with scientists: **most professional computer software isn't very good**. The code inside your laptop, television, phone or car is **often badly documented, inconsistent and poorly tested.**

... And you scientists generally think **the code you write is poor**. It doesn't contain good comments, have sensible variable names or proper indentation. It breaks if you introduce badly formatted data, and you need to edit the output by hand to get the columns to line up. **It includes a routine written by a graduate student which you never completely understood**, and so on. Sound familiar? **Well, those things don't matter.**

That the code is a little raw is one of the main reasons scientists give for not sharing it with others. Yet, software in all trades is written to be good enough for the job intended. So if your code is good enough to do the job, then it is good enough to release — and releasing it will help your research and your field.



Computer modelling of carbon **nano**materials

Manuel Melle Franco
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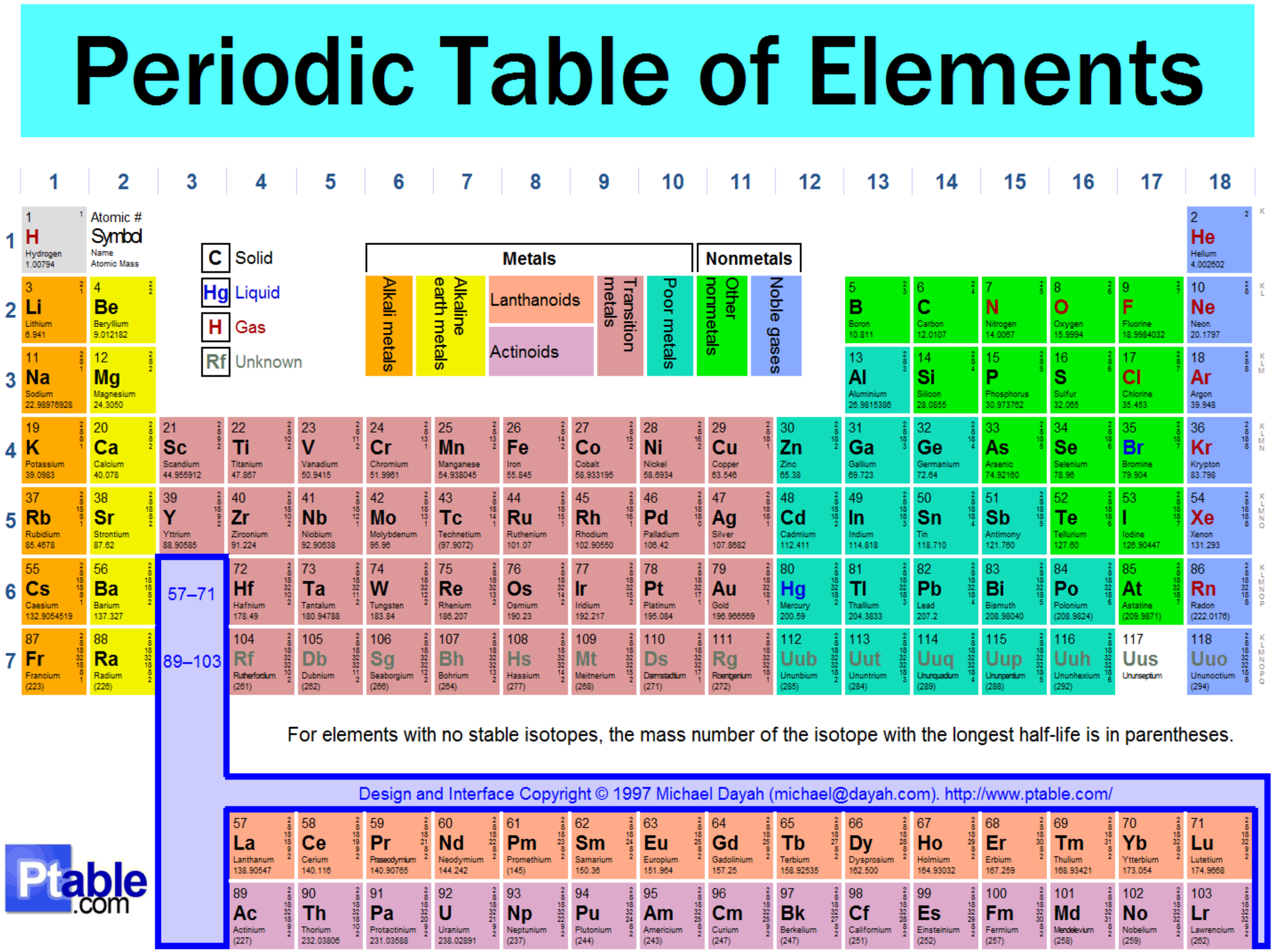
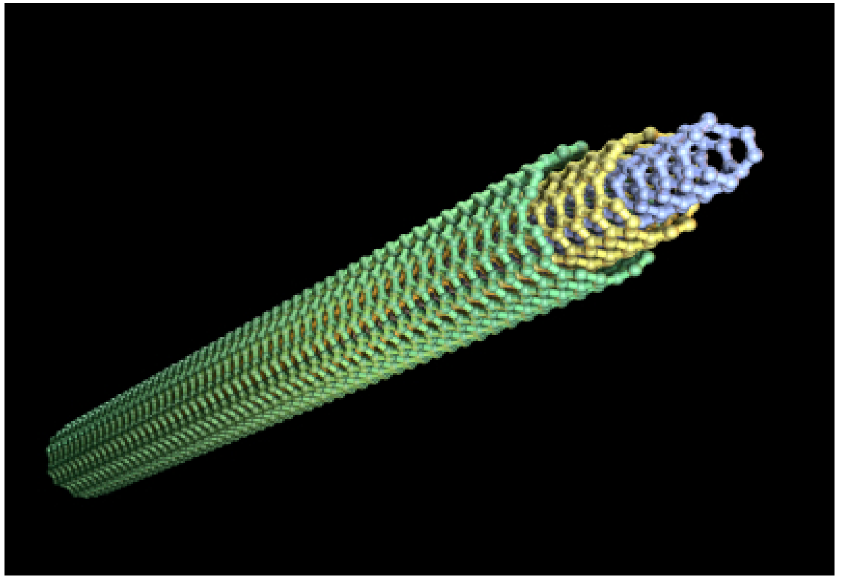
Nanotechnology **(smallest tech!!!)**

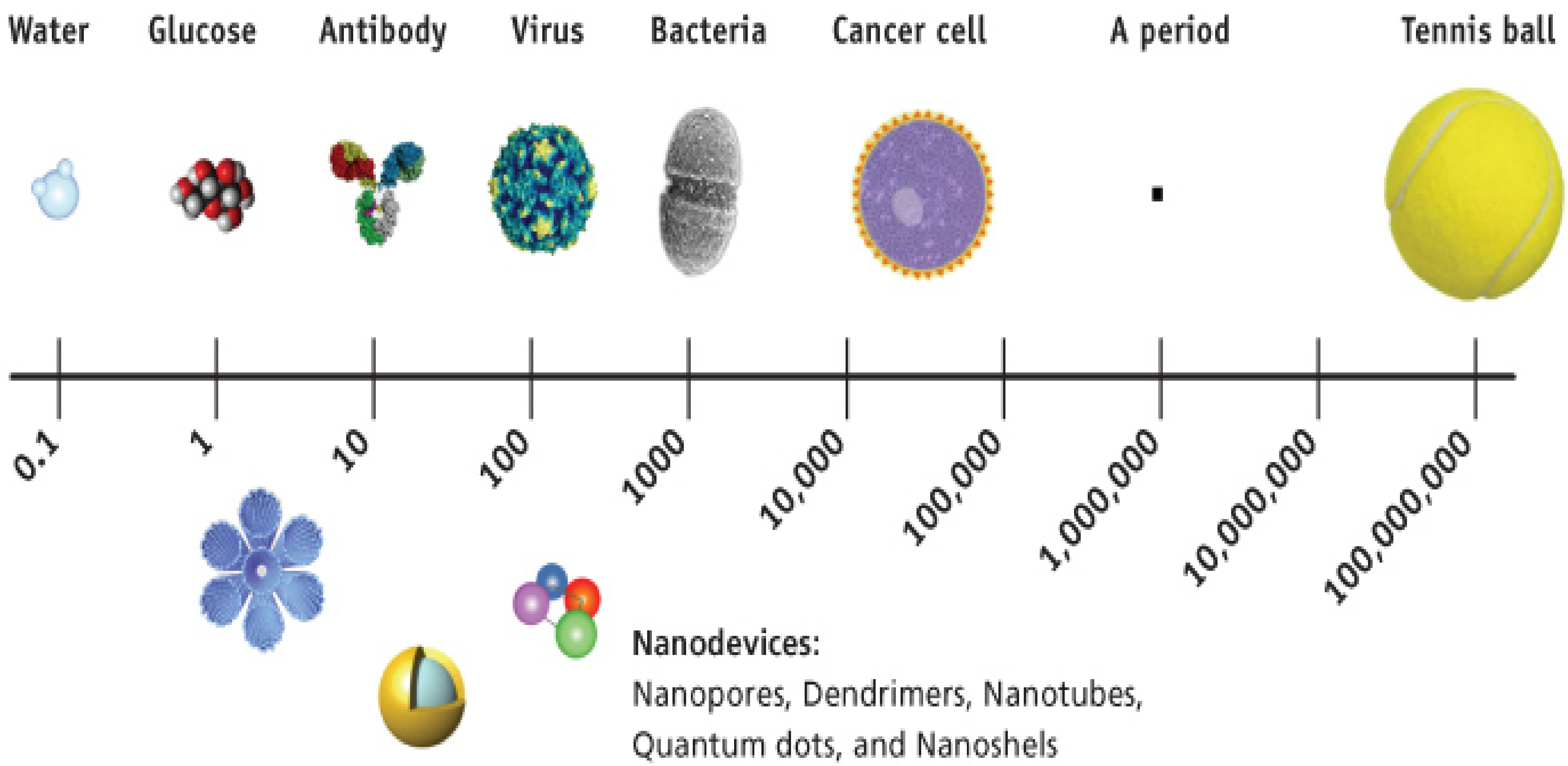
- **Nanotechnology** is the manipulation of matter on an atomic and molecular scale (**Wikipedia).**



Nanotechnology

- Nanometer
  - 10^{-9} meters (1 millionth of 1 mm)
  - 1-2 atom diameters
- Nanoobjects < 1000 nanometers in at least one dimension, i.e. carbon **nano**tube:
  - long millimeters: macroscopic (axis)
  - thick nanometers: **nano** (diameter)





Nanometer **Chart**

Can we see nanobjects?

- If we are to manipulate atoms we have to control and know their positions in space! **SEE THEM!**

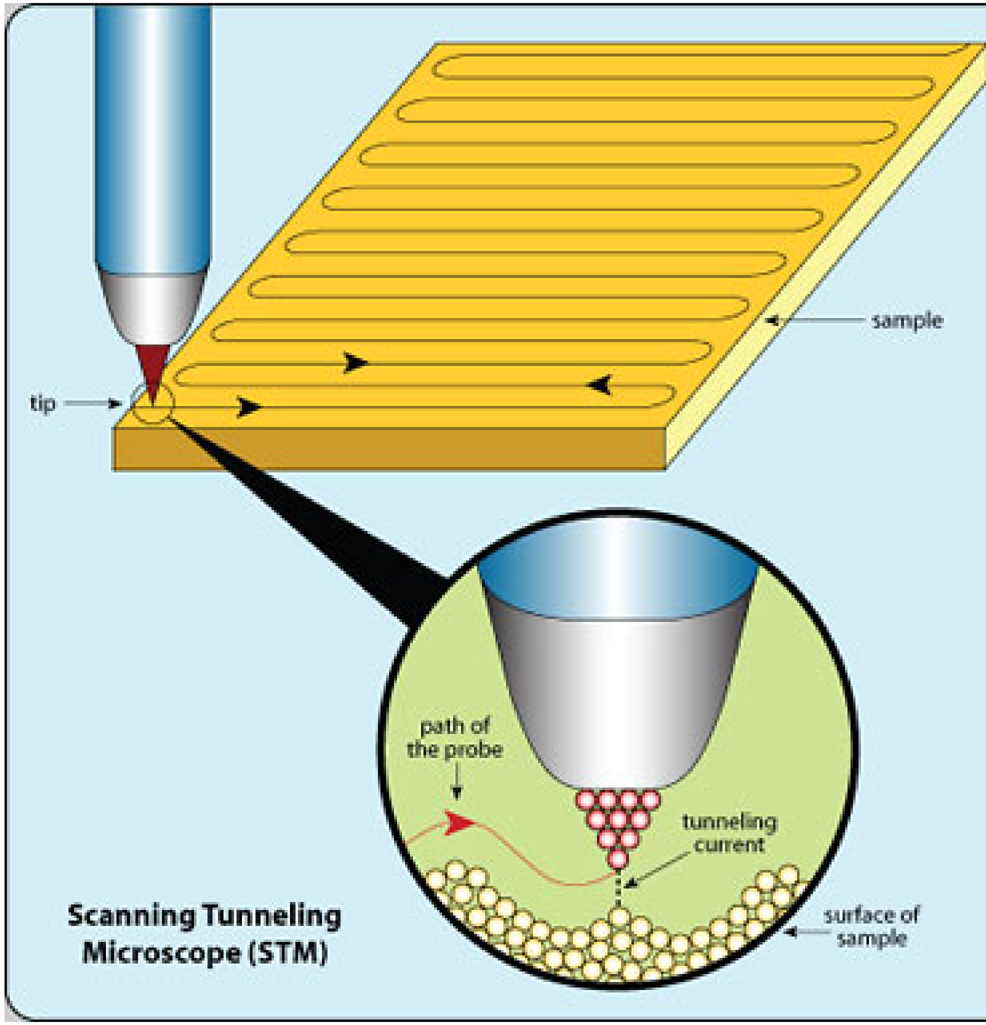
- can we see atoms with microscope?
  - Using visible light?
    - NO, best resolution with visible light, 200 nm (atom ~ 1 nm)
  - Using electrons?:
    - Yes easy to have electrons with shorter wavelenght than light (up to Atomic resolution!!!)

Start of Nanotechnology

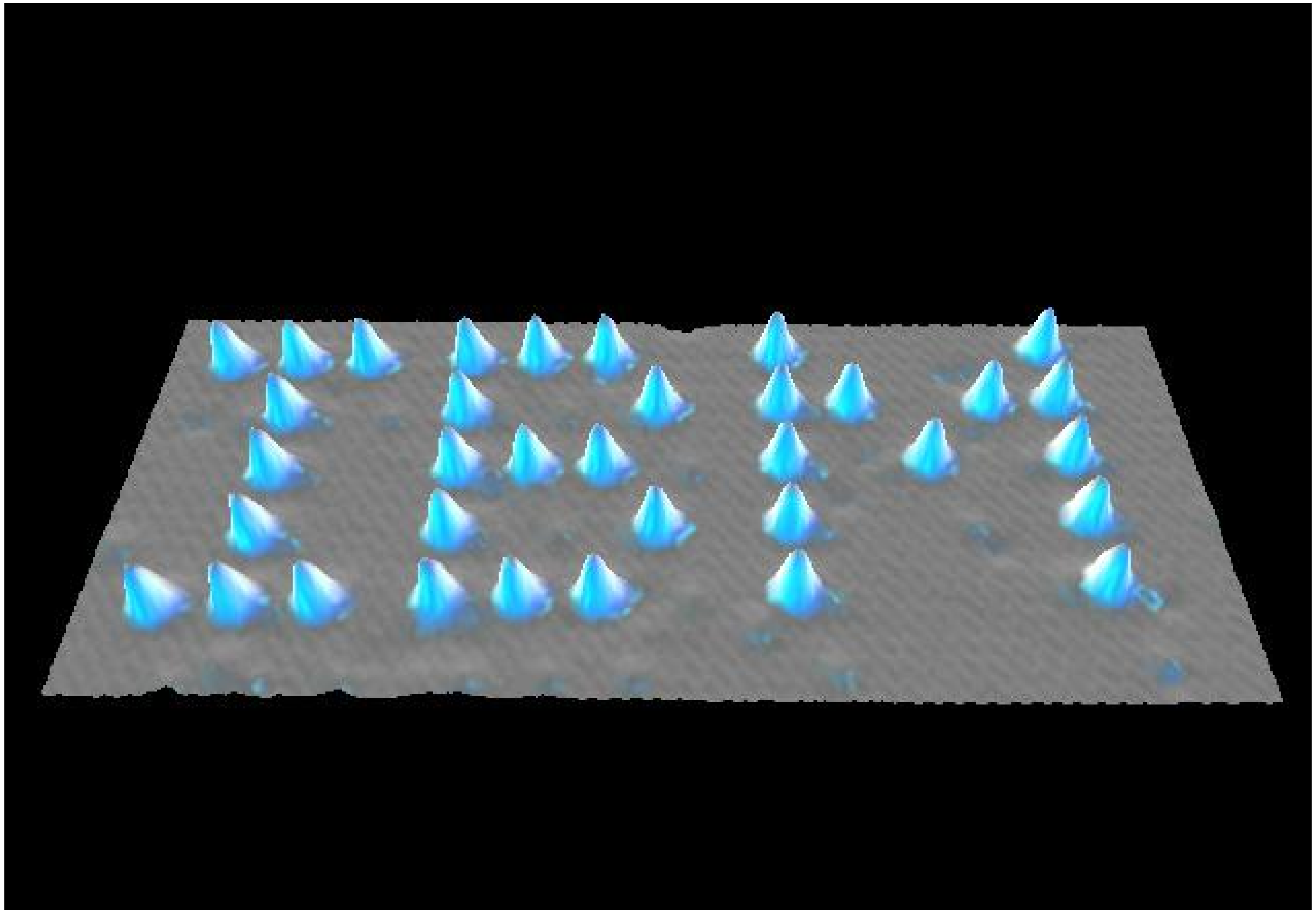
- In 1986 single atoms could be directly *imaged* for the first time with Scanning Tunneling Microscopy **(STM)**
- **MAJOR BREAKTROUGH:** Gerd Binnig and Heinrich Rohrer, Nobel Prize of Physics **same year!**
- Description (STM FOR dummies): http://www.nobelprize.org/nobel_prizes/physics/laureates/1986/press.html

Scanning tunneling Microscopy

- a mechanical device is used to sense the structure of a surface like **braille-reading** (the reader's fingers that detect the impressed characters).
- the surface is traversed by a probe a distance from the surface (to not alter it) the vertical movement of which is recorded.



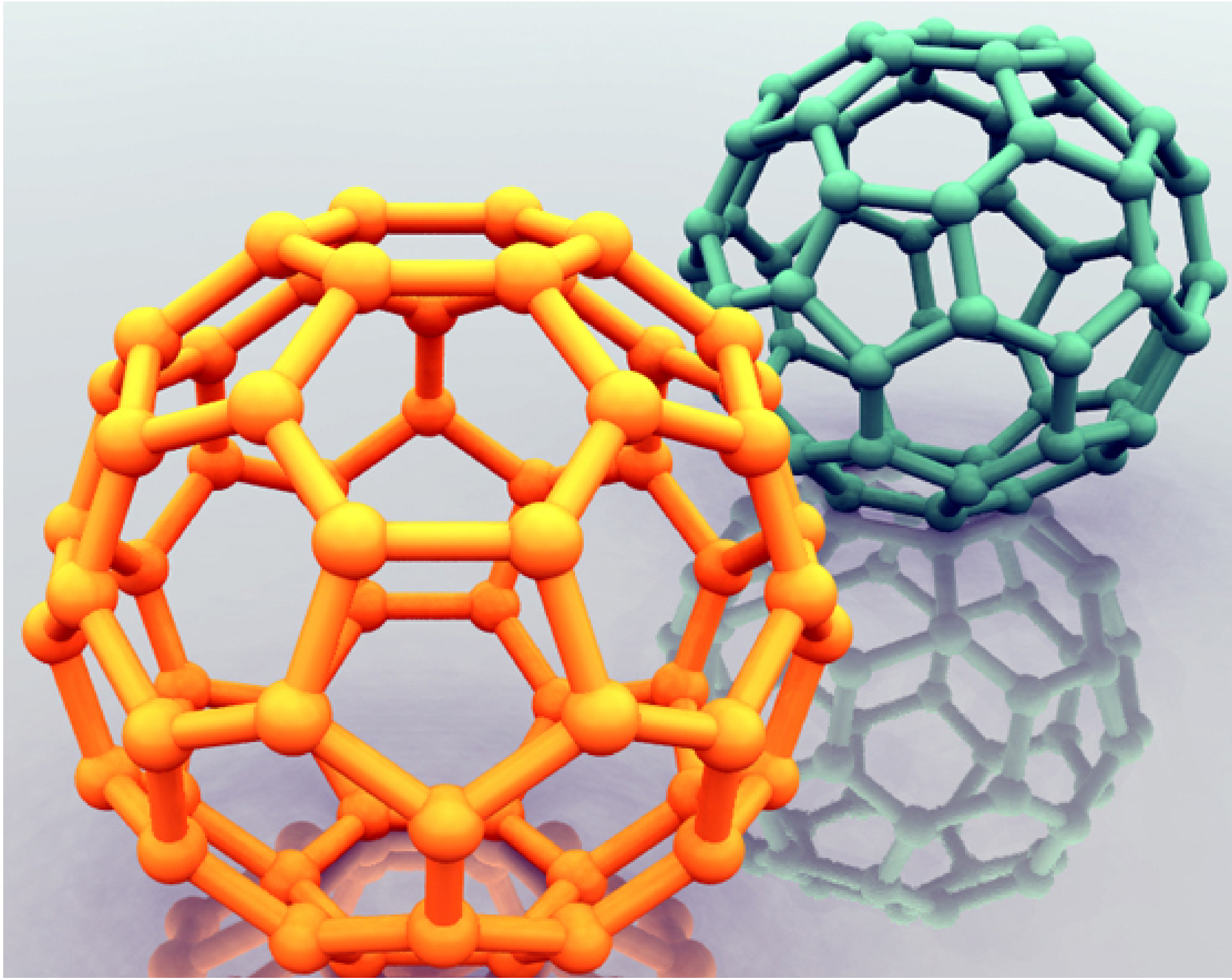
The world smallest corporate logol



1989 – first to controllably **manipulate individual atoms** on a surface, using the **STM** spell out “I-B-M” by positioning **35 xenon atoms** [on a Nickel (110) surface]

STM "images" grid data of the surface

D.M. Eigler, E.K. Schweizer. **Positioning single atoms with a scanning tunneling microscope.** *Nature 344, 524-526 (1990).*



Carbon Nanotechnology!

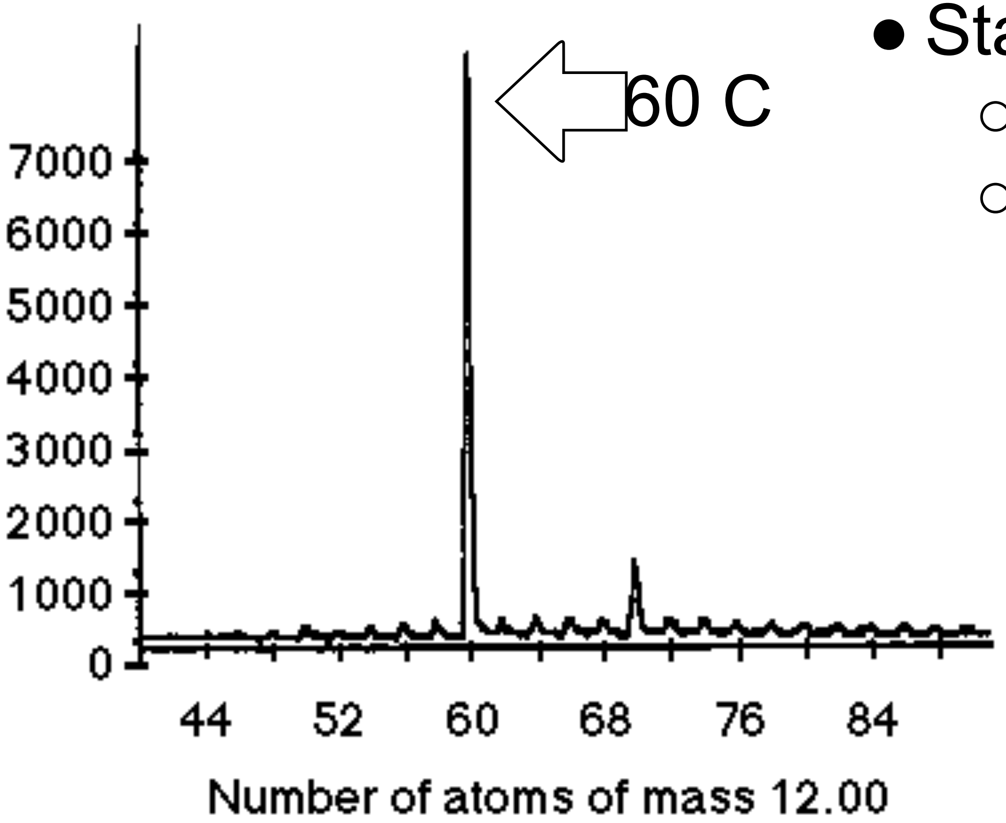
Carbon nanotechnology started in space!

- In **1985**, British chemist Harry Kroto was puzzling over strange chains of **carbon atoms** that could be **detected billions of kilometres** away in space by **radiotelescopes**. He thought that these chains might form in conditions that are found **near** red giant **stars**. **[Science is AMAZING isn't it?]**

- Kroto visited the US laboratory of Richard Smalley and Robert Curl, who were studying 'clusters' – aggregates of atoms that only exist briefly. Together they attempted to **create high-temperature conditions in the laboratory, conditions similar to those near red giants**. They vaporised graphite with a powerful laser in an atmosphere of helium gas.

Buckyballs history

- The did mass spectra of the sample and found a very large peak for **60 C atoms** (with another smaller for 70 C atoms), that was the first buckyball [(Nature 318, 162)]



What was the molecular structure?

- Stable (observation)
    - Spherical (from chemistry)
    - Symmetrical (speculation)

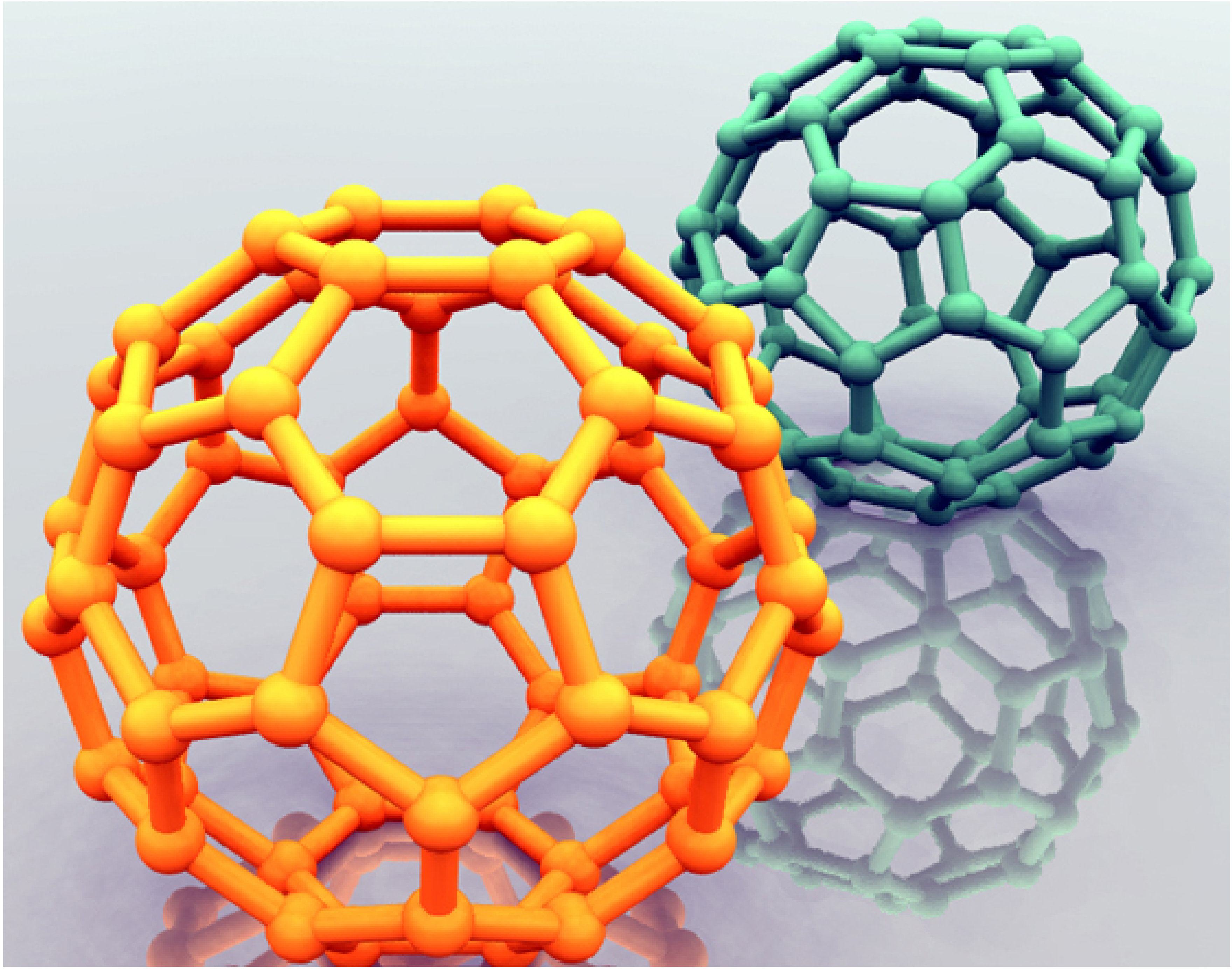
Finding the structure?

What was the structure?

Very difficult, as last resort **a paper model by cutting out paper pentagons and hexagons in which he tried to stick them together so that the figure had 60 vertices (60 atoms)**. Smalley found a sphere made out of 12 pentagons interlocking 20 hexagons to make **a football ball**. That was actually the C_{60} structure, as found later, and the **nobel prize for 1996**!

Apparently Smalley did the interpretation in 11 days!

He was very lucky: graph theory gives another 1811 possibilites. But C60 is the most symmetrical one!



Fullerene C_{60} 1nm Diameter spherical molecule

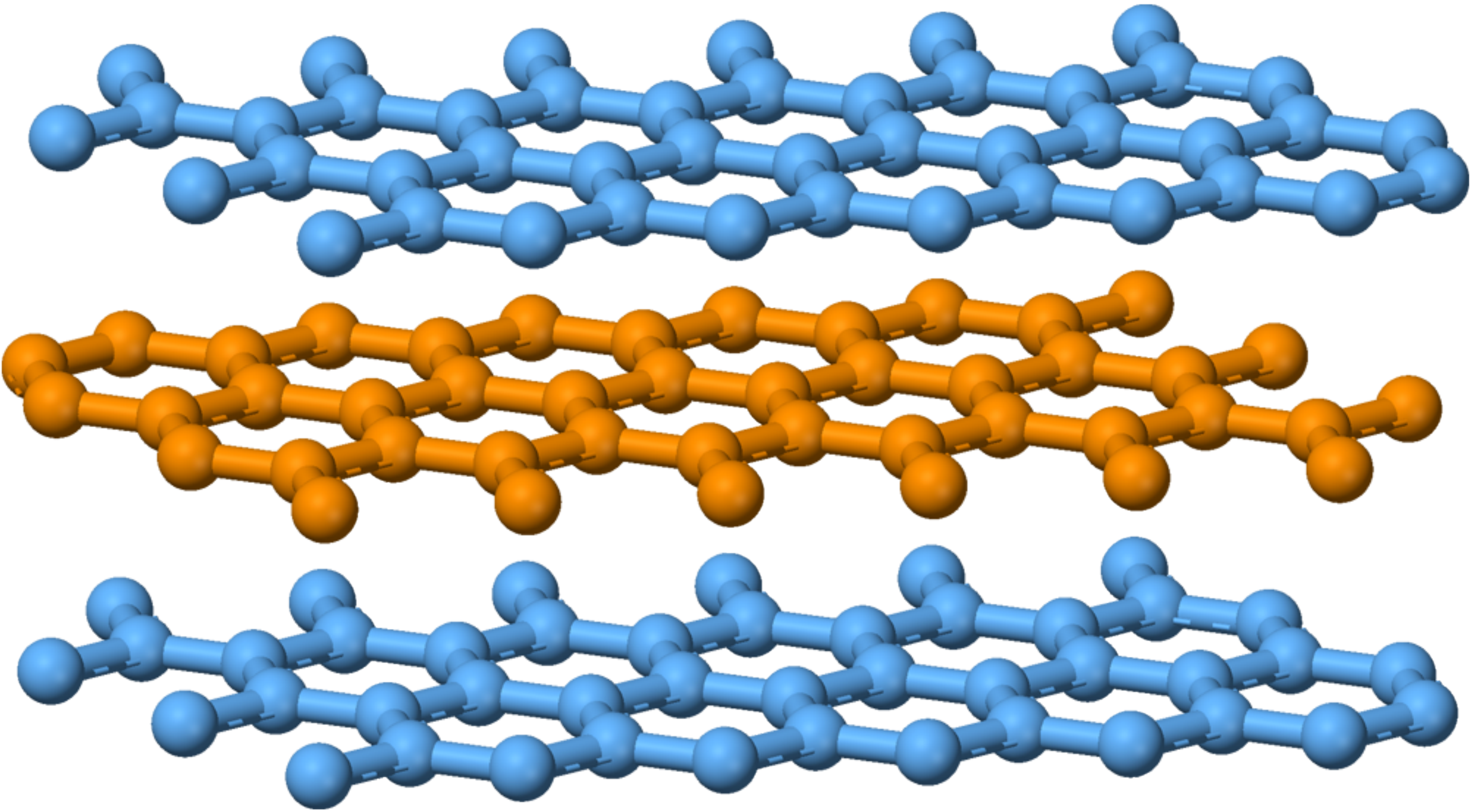
Graphite

- THE Mineral made of carbon
- So, found in large quantities in natural form
- Thermodynamically **the most stable form of carbon** (wait long enough all diamond will turn into graphite!)

Many historical and contemporary technological applications:

- pencils!
- electrical applications (lamps, electrodes, first speakers and microphones...)

Graphite Structure

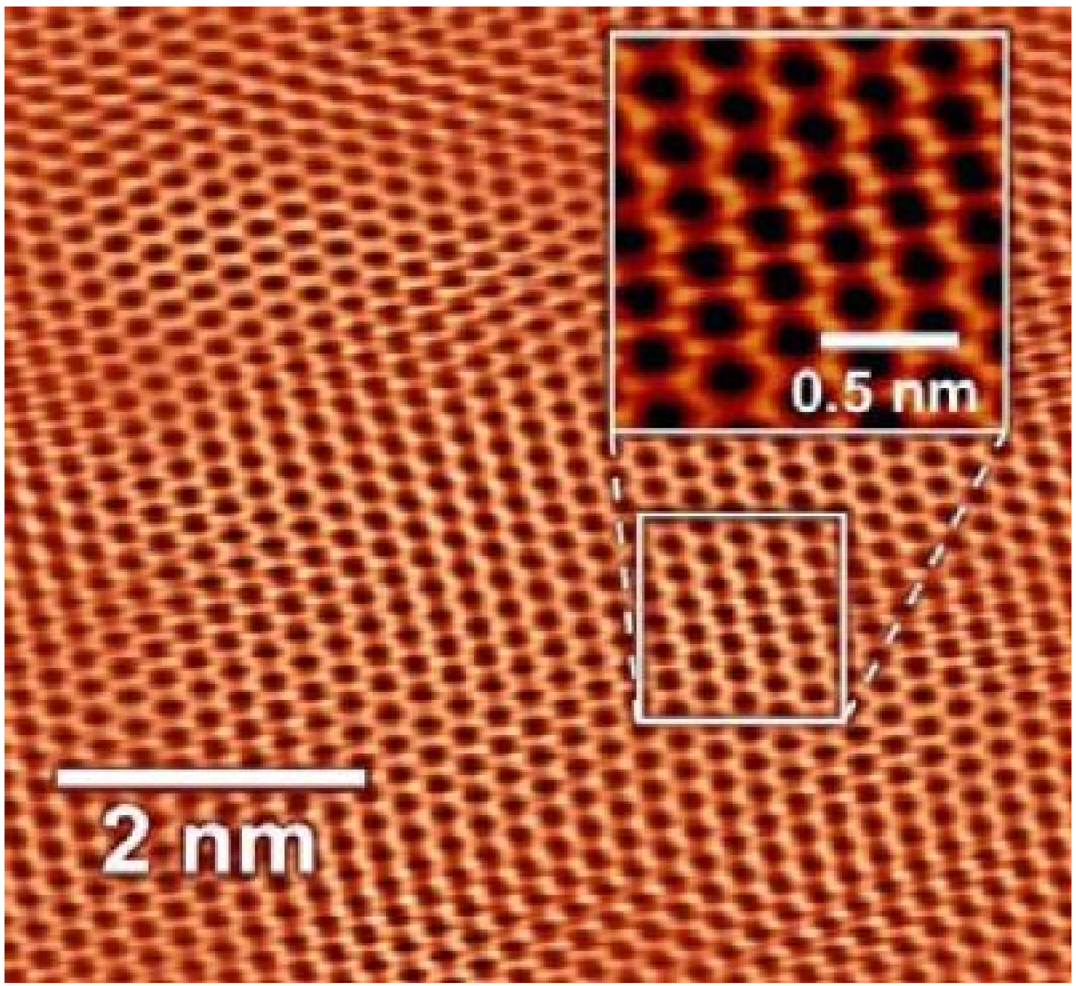


Layered structure, carbon (sp^2) layers 0.35 nm apart

The most stable form of carbon (diamond goes to graphite with time!!!)

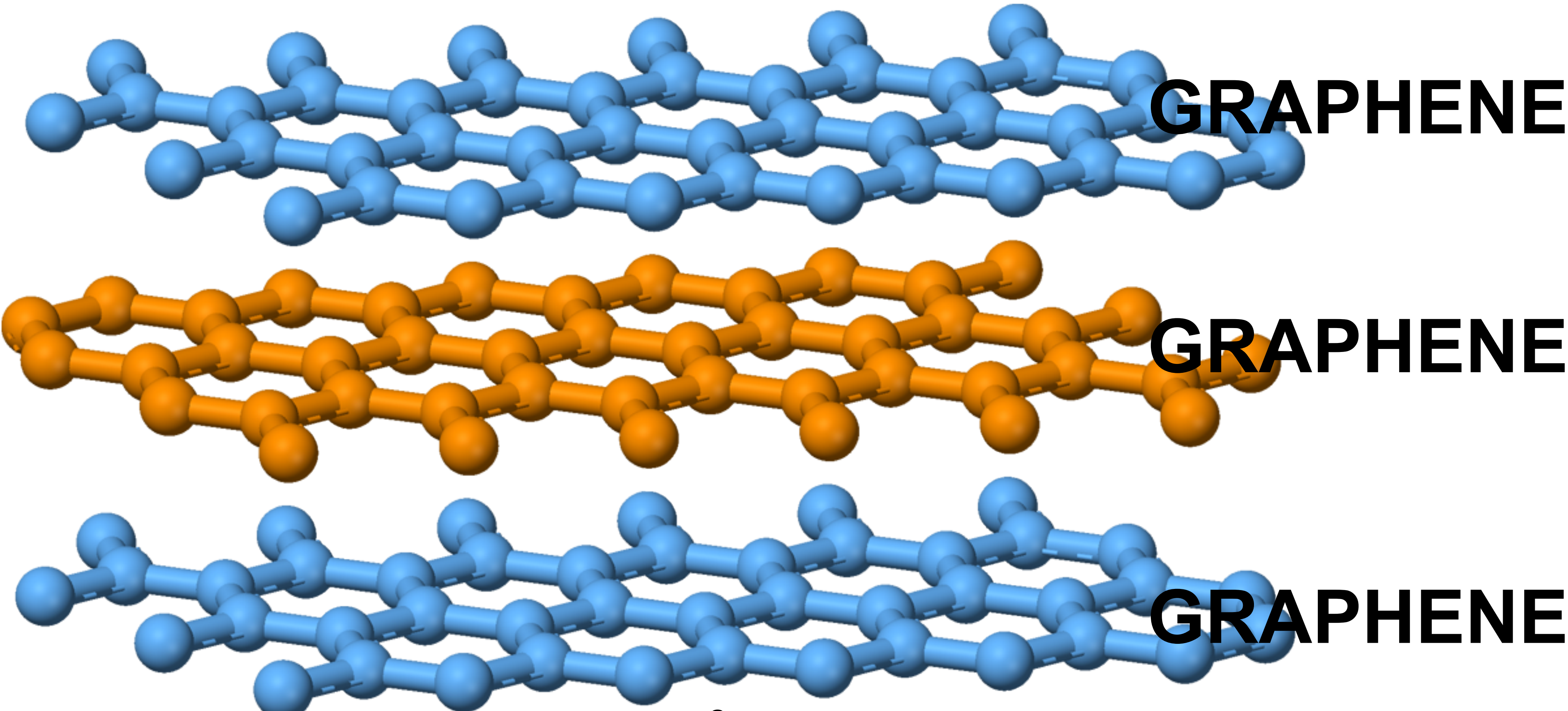
Graphite surface

- Atomic resolution STM image (easy to do in graphite!)



- Electron Microscopy great BREAKTROUGH 25 years but still a very difficult technology!
-Fullerene seen in microscopy at atomic resolution only RECENTLY (good for regular flat surfaces)

Graphite/Graphene Structure



Layered structure, carbon sp^2 layers 0.35 nm apart, **graphene 1 atom thick 2D materials (Physics NP 2011)**
Nuno Peres (U. Minho!) collaborator of NP winners!

The finding of graphene

Graphene -> 1 layer graphite

In **2004**, graphene was obtained first by **mechanical exfoliation** of graphite. They used **Scotch tape** to repeatedly split graphite crystals into increasingly thinner pieces. The tape with attached optically transparent flakes was dissolved in acetone and, after a few further steps, the flakes including monolayers were sedimented on a Si wafer. Individual atomic planes were then hunted in an optical microscope. First of a series of science and nature papers on the topic!!!!

2004? why?

Before it was "impossible"!!!! (more on a minute)

why it was impossible?

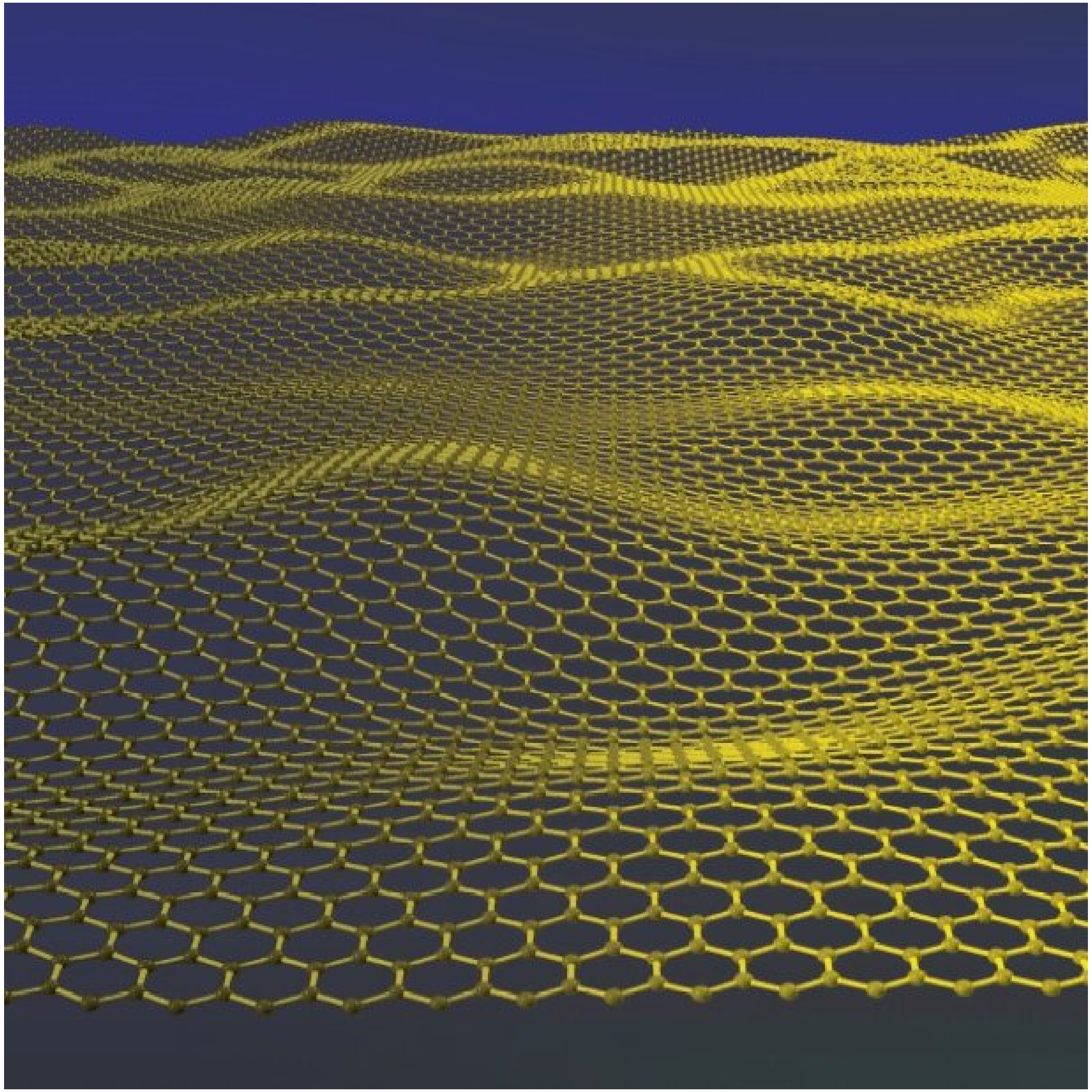
- **Perfect two-dimensional crystals cannot exist in the free state!**

Experimental evidence it was 1 atom thick material, so not impossible!

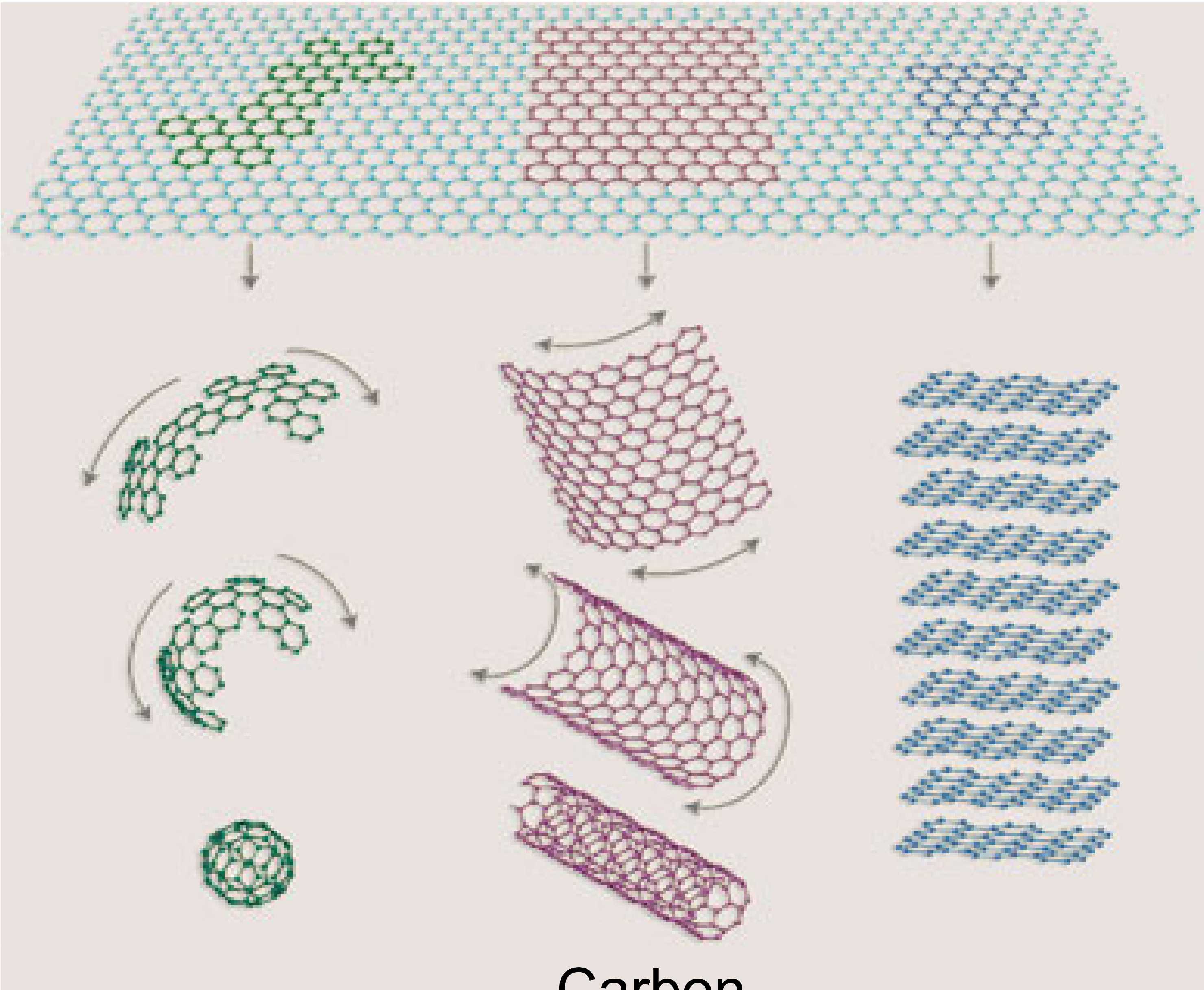
HOW?

graphene structure

- ondulated/wavy structure!
- it is not 2D but 3D!!
- Unexpected, quantum chemistry predicts graphene to be FLAT!



Carbon **nano**materials



Buckyball

Carbon
Nanotube

Graphite

Graphene!

Common chemical bricks (Csp2!)

They all exist and are routinely synthesized!

Research in carbon **nano**materials

- Fullerenes, discovered **1985** > 10000 research articles
- Carbon nanotubes, discovered **1991**, > 70000 articles.
- Graphene, discovered **2004**, > 10000 articles.

Two nobel prizes:
- chemistry (1996)
- physics (2011)

Discovered = Clearly observed (latest development in high atomic resolution microscopy, crutial tool for nanotechnology)

1 hundred thousand PR papers, in 25 years, extremely active fields of research, why?

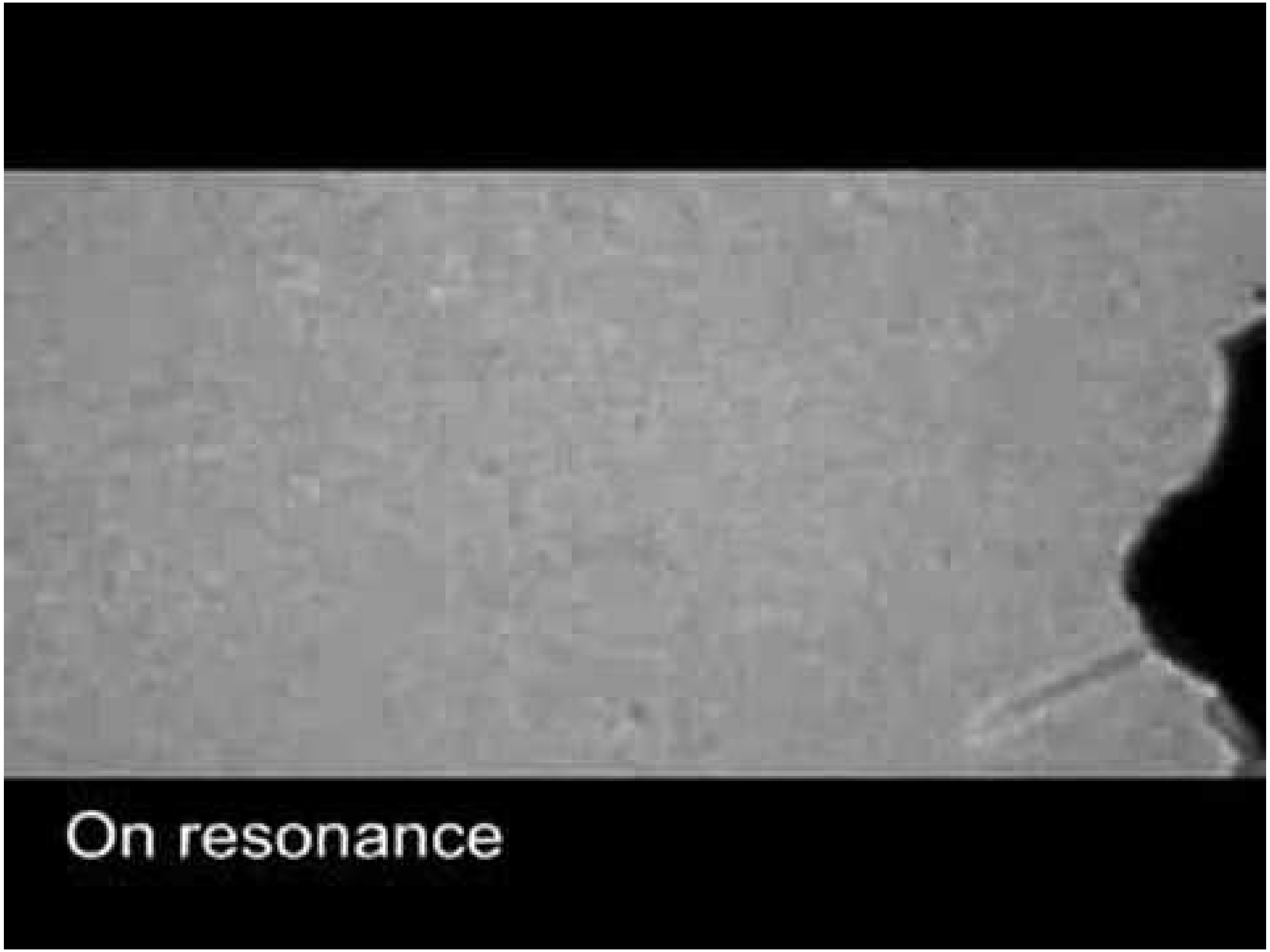
HIGH TECHNOLOGICAL POTENTIAL for **NANOTECHNOLOGY (and they are difficult and fun!)**

Carbon NanoTechnology, Sci-Fi? The Nanoradio

A few amazing devices have appeared recently in literature involving the Professor Zetll group in Berkeley and carbon Nanotubes. Specially striking, the nanoradio (K. Jensen, J. Weldon, H. Garcia, and A. Zettl. Nano Letters 7, 11, 3508-3511 (2007) a **fully functional fully integrated radio receiver made with a single nanotube**.

nanodevices

"Good vibrations..." (VIDEO!)



Nanoradio Details

We have constructed a fully functional, fully integrated radio receiver, orders-of-magnitude smaller than any previous radio, from a **single carbon nanotube**. The single nanotube serves, at once, as:

- antenna
- tuner
- amplifier
- demodulator

The antenna and tuner are implemented in a radically different manner than traditional radios, receiving signals via high frequency ***mechanical*** **vibrations of the nanotube** rather than through traditional electrical means.

Carbon Nanotechnology, NOT SciFi, everyday life?

Nanoradio: amazing, yet **proof of concept (i.e. experiment shows it can be done, but it is VERY DIFFICULT to do so!)**

industrially produced? NO, to the best of my knowledge!**!!!!!**:

- Fullerenes used for plastic solar cells (not commercially yet!!!)
- No real world application for graphene (high potential for nanoelectronics, **graphenium inside**).
- Carbon nanotubes are used JUST like carbon fibers for reinforcing COMPOSITE materials

- ALL OF THEM FOR **PLAIN MARKETING!!**

Why not **industrial** applications yet?

- **Carbon nanotechnology is very difficult**:
  - polidispersity (intrinsic):
    - all materials made with same building blocks (Csp2):
      - difficult to produce controlled materials
      - characterization problems
      - product separation problems

- No solution yet!!!!
- It needs complex **JOINT experimental and theoretical techniques** and analysis **GOOD FOR ME!**

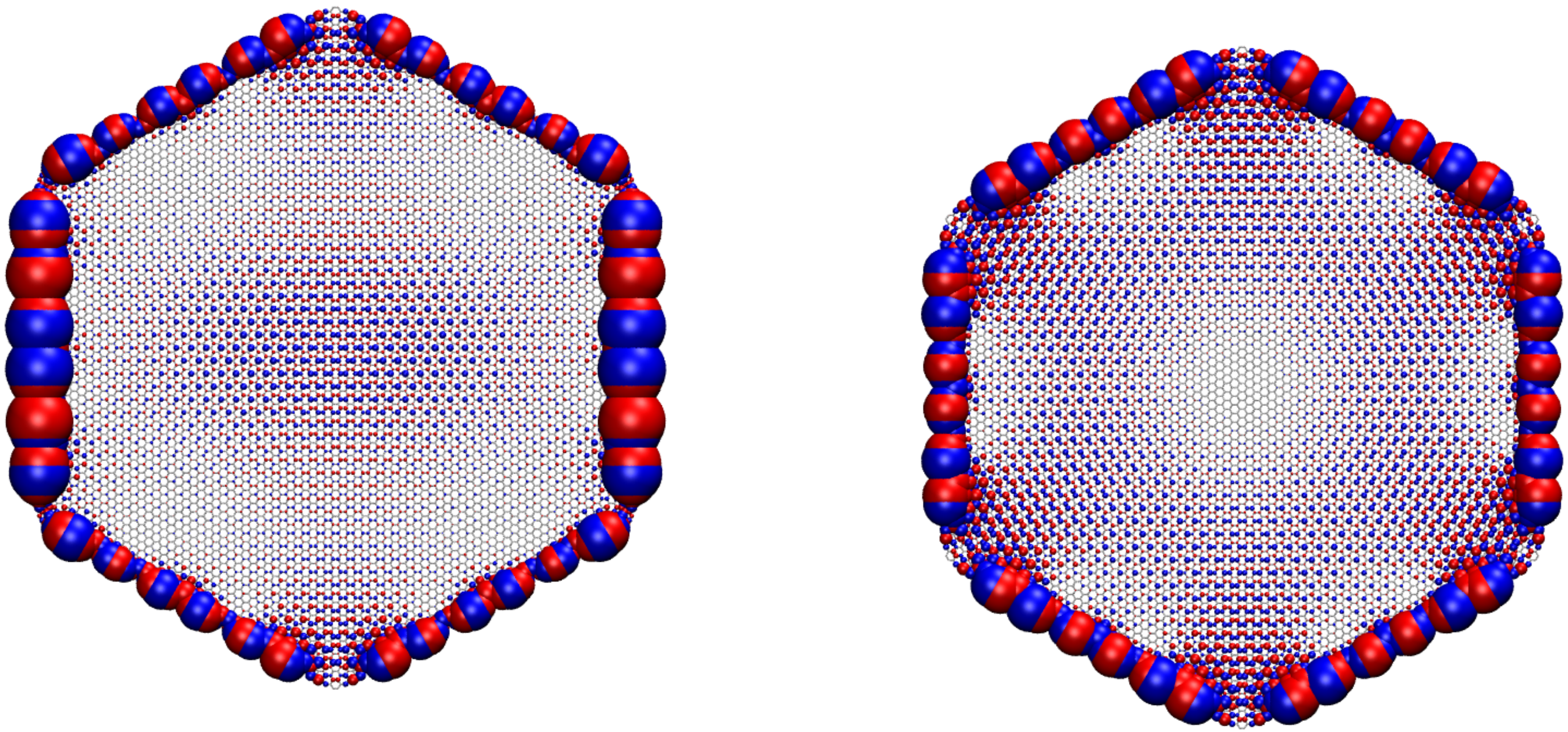
Computer models aid COMPLEX experiments (I)

Electronic properties of carbon nanomaterials!

Developing QM software for carbon

- Quantum chemistry models are based on matrices
- Matrices have sizes proportional to the number of electrons
- C has 6 electrons, but most interesting properties depend only on 1 electron:
  - 1 electron matrices are 1/36th in size so allow for larger sizes
  - Still, memory use (full matrix):
    - 10^4 electrons/C atoms -> 0.74 GB memory (Done)
    - 10^5 electrons/C atoms -> 74 GB memory (doable)
    - 10^6 electrons/C atoms -> 7400 GB (indirect methods, distributed memory)

Orbitals of 9600 C/e^- graphene flake (calculation only takes 24 hours!)



HOMO LUMO

Each DOT in graph is AN ATOM!!!!

Balls represent diffuse electrons -> these borders are very reactive! IMPOSSIBLE WITH MOST SOFWARE

Computer models aid COMPLEX experiments (II)

3D structure of Graphene (on going very preliminary)

3D structure of Graphene

- From results of 2011 master students of CPD modified algorithm way to make very fast calculations of graphene in serial computers
- Results with molecular dynamics give an stable wavy structure at room temperature (5 * 10**4 atoms 1 ns (10^6 iterations, in 24 hours):

- **PRELIMINARY**, it is reproducible, but not in all conditions, yet, :(
- Is it real (physics) or arising from a numerical artifact ? very subtle computation!!!
- **It scales linearly so I am trying now much larger systems**

Virtual/in silico experiments

Do things that are extremely difficult impossible experimentally and see what happens

Very challenging: **how to asses the quality of models without experiment?**

Research III Virtual/in silico experiment

Nanonozzles (MD!!! what you study in this course!)

Ejection Dynamics of a Simple Liquid from Individual Carbon Nanotube Nozzles

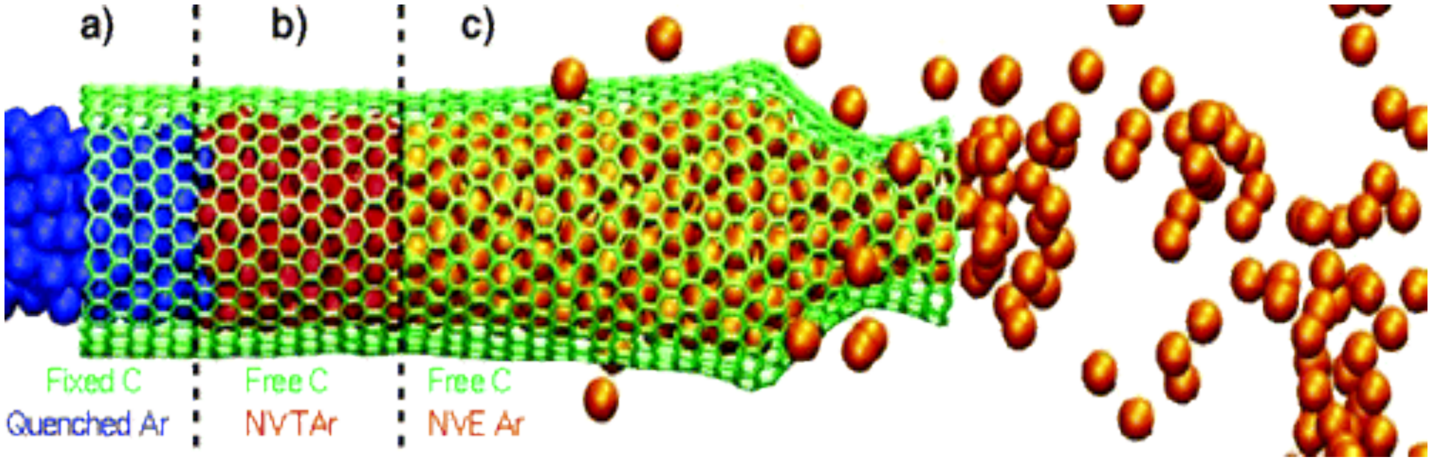
Manuel Melle-Franco*[‡] and Francesco Zerbetto*[‡] Nano Lett., **2006**, *6* (5), pp 969–972

Molecular dynamics simulations show that the flow of a high pressurized atomic liquid inside carbon nanotube "pipets" occurs in one-atom-thick well-defined laminae. Fluxes and velocities at ejection are a function of the inlet diameter and the type of outlet. In the conditions investigated here, the force of the ejected liquid is similar in value to that of biomotors, while the output per second is of the order of picoliters.

Nanonozzles Virtual Experiments

Liquid Argon at hight pressure trough carbon nanotube nozzle, NANO-FLUIDICS!

- 2 years programming
- 2 weeks simulations



Specific MD software to do this, very challenging algorithms and physics. **VIDEO!**

Research IV Virtual/in silico experiments
BIO-nanotechnology

A computational analysis of the insertion of carbon nanotubes into cellular membranes

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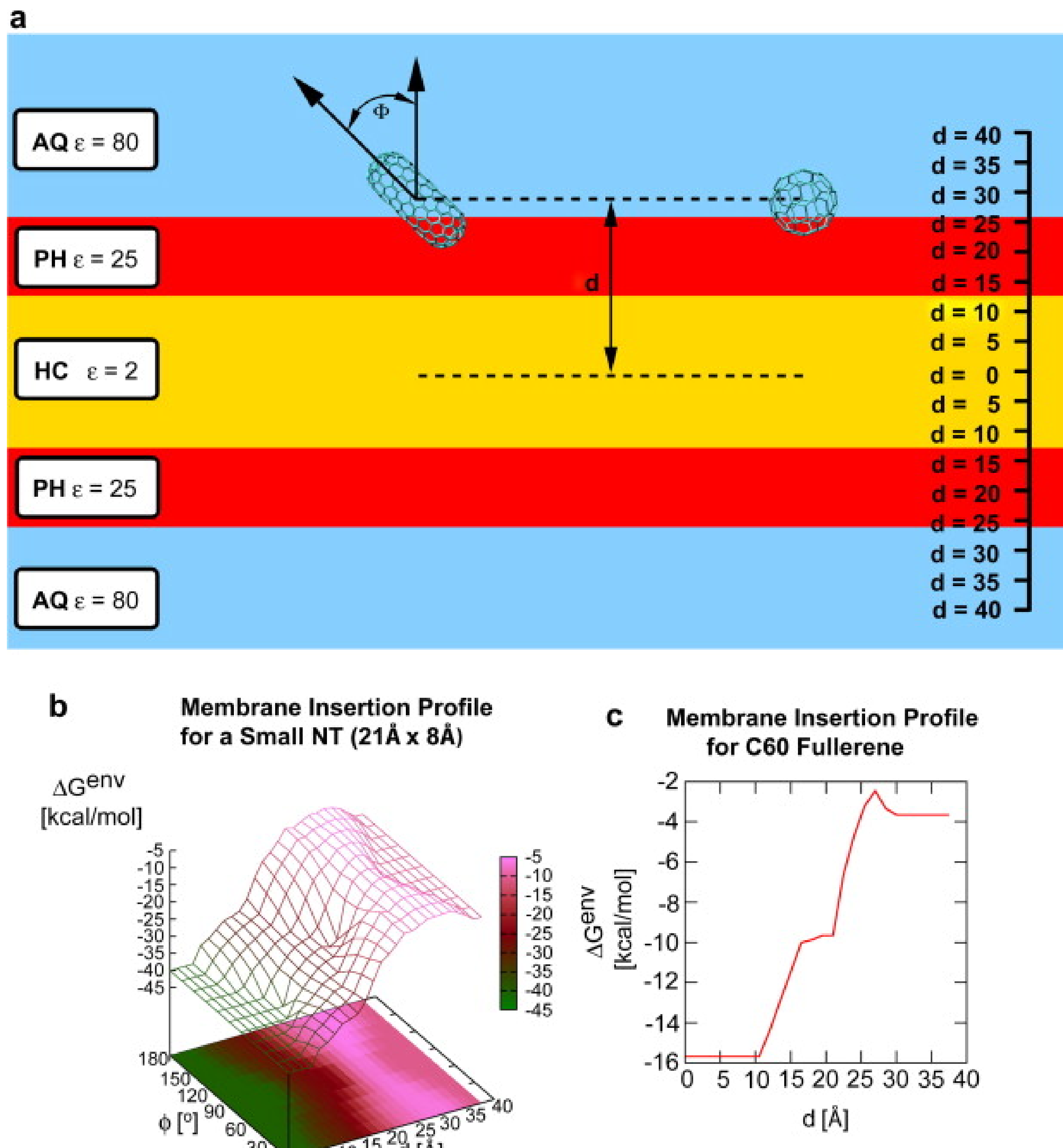
Carbon nanotubes have been proposed to serve as nano-vehicles to deliver genetic or therapeutic material into the interior of cells because of their capacity to cross the cell membrane. A detailed picture of the molecular mode of action of such a delivery is, however, difficult to obtain because of the concealing effects of the cell membrane. Here we report a systematic computational study of membrane insertion of individual carbon nanotubes and carbon nanotube bundles using two entirely different and unrelated techniques. First a static scan of the environmental free energy is carried out based on a membrane mimicry approach and different insertion geometries are assessed. Then the dynamics is investigated with a coarse-grained approach that was previously used in the study of the integration dynamics of nanoparticles into the bilayer. The results of both models point, for unfunctionalized carbon nanotubes, at a preference for the horizontal orientation inside the internal hydrophobic layer of the cell membrane. Finally, the energetics of the formation of bundles of carbon nanotubes is studied. The cellular membrane promotes aggregation of carbon nanotubes in its hydrophobic core and modifies the structural stability of the bundles.

Nanocarbon and membranes

- Membrane (Spanish flag)
- Energetics for a C_{60} and small nanotubes. entering the membrane (yellow apolar part: MORE STABLE than outside)



Nanotoxicity

- Nanotoxicity is fundamental issue in nanotechnology!!!!
- Exp. PURE fullerenes and nanotubes are VERY TOXIC for cells!!!
  - High citotoxicity -> molecular cause:
    - Fuls and CNTs **spontaneously** enter membranes and **accumulate** there **(VIDEO*)**

***:Mesoscopic MD Simulations, not ATOMIC RESOLUTION (sizes and timescales!!!!)**

Summary I

- Computer simulation is a very powerful tool for chemistry and physics of nanomaterials
- Very complex problems need specific software and approaches
- Needed to complement / explain / justify experimental results of nanomaterials
- Nowadays ALL state of the art studies HAVE ALSO a computational part!!!!
- Can be used, with care, to do VIRTUAL , impossible, experiments

Summary II (for you!)

- Computer modelling is a FUNDAMENTAL TOOL FOR physics and chemistry !!!!!
- HPC is fundamental for computer modelling!!!

More computing-like

Compressed sensing!

Compressed sensing

Using a mathematical concept called sparsity, the compressed-sensing algorithm takes **very noisy** data and transforms them into clean data.

It turns out that out of all the HUGE possible reconstructions, the simplest, or sparsest, image is almost always the right one or very close to it.

With a Photograph:

h

1

Compressed sensing

Compressed sensing used for DSP and image processing:

- Fourier transforms with much less input data

- Can it be used for molecular modelling?
  - Indirectly, FT with less data, implies less calculations

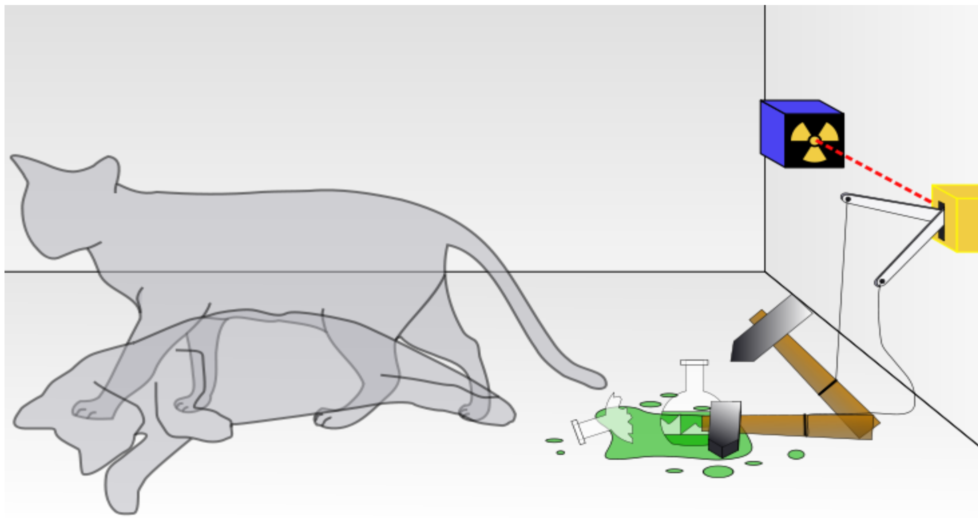
Very challenging!!!
Many interesting and amazing possibilities!

Final Comments

Short snapshots of what we do, we do many other things. **Work with chemists, physicists, biologists, mathematicians, and, now, directly with computer scientists!**

I am an **active researcher**, I also direct, supervise and coordinate but most of my time **I DO RESEARCH myself, I am very curious and is FUN, that is why I do it!**

Schrödinger's cat in box

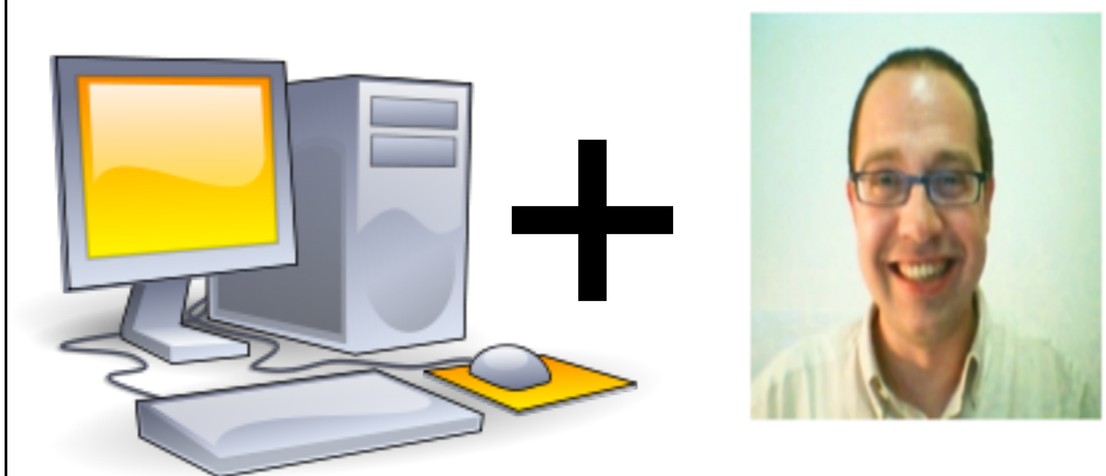


One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter, there is a tiny bit of radioactive substance, so small that perhaps in the course of the hour, one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges, and through a relay releases a hammer that shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts. It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself, it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks

Paradox thought experiment in which a cat, based on a QM event, is 50% dead and %50 alive!

Manuel in a box

internet



50% dead 50%
alive SOMETIMES TOO!

Science

Feel free to contact me for any reason!

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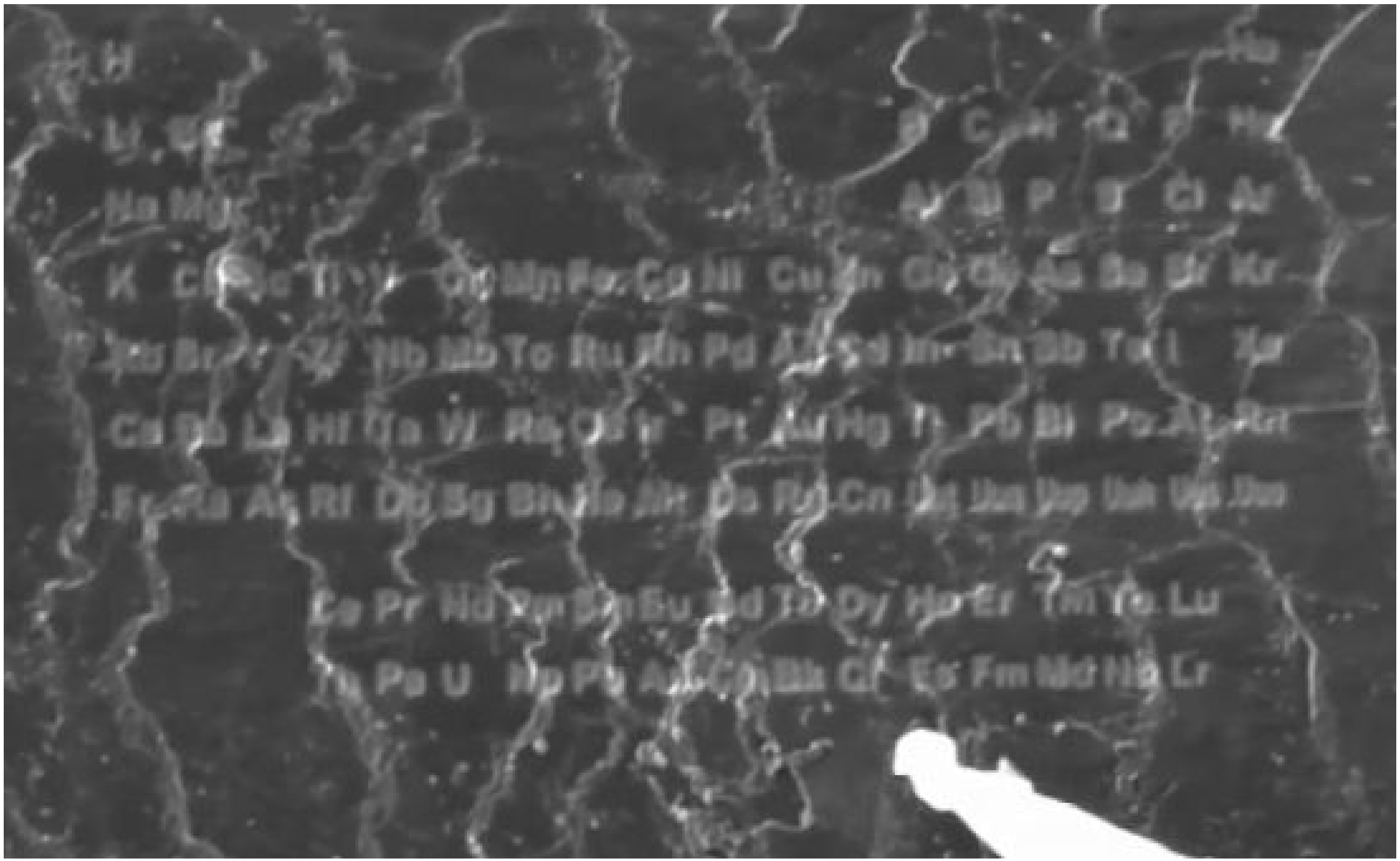
- Co-workers all over the world!
- **CCTC (DI UMINHO)** for hiring me to do more exciting science!!!

thank you for your time, :D
hope it was worth it!

Smallest Periodic table!!!!!



0.046 mm

0.088 mm

On a human hair!!!