Taller 5: Programa Omicas 2021 Fundamentals of Nanoscale Science and Engineering

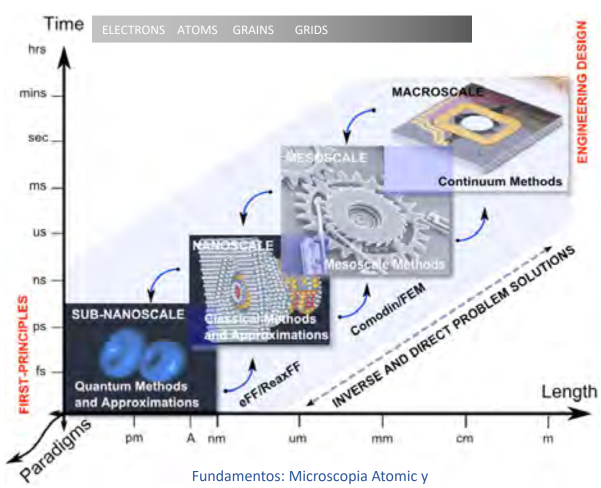
Andrés Jaramillo-Botero

PUJC: Prof. Titular; Director Cientifico, Programa Omicas; Director, Doctorado en Ingenieria y Ciencias Aplicadas (FIC)

Caltech: Director, Multiscale Science (MSC), division de Quimica e Ingenieria Quimica

1

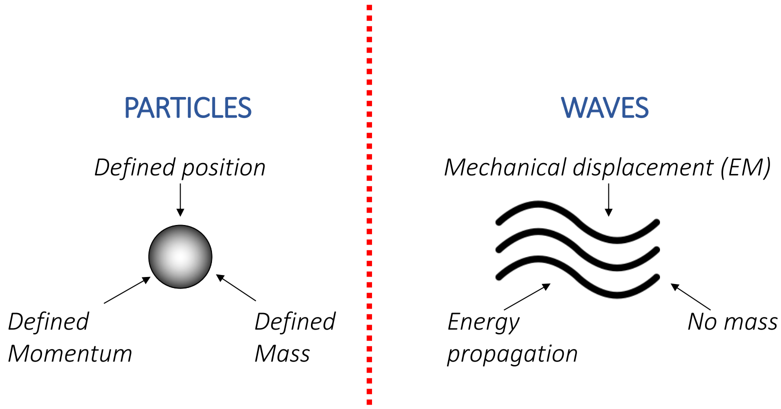
Everything is made of atoms, i.e. all properties depend on atomic composition and structure



Fundamentos: Microscopia Atomic y Electronica, 2021

2

Diverging physical ideas: <1900<



Fundamentos: Microscopia Atomic y Electronica, 2021

3

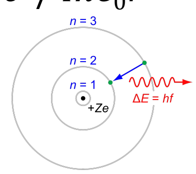
Historical precedents: summary

(1900's) Planck: energy occurs in quanta — $E = hv = hc/\lambda$

(1913) Bohr: atomic model — $m_e v^2/r = e^2/4\pi\varepsilon_0 r^2$

(1920's) Einstein: mass and energy are exchangeable — $E = mc^2$

(1921) de Broglie: wave-particle duality — $h/\lambda = \rho$



(1925) Schrödinger: electronic wave equation — $H(R)\psi(R) = E\psi(R)$

(1927) Heisenberg: adds uncertainty principle

"What is the probability distribution governing the positions?"

(1959) Feynman: (Caltech) Nanotechnology is born

Fundamentos: Microscopia Atomic y Electronica, 2021

4

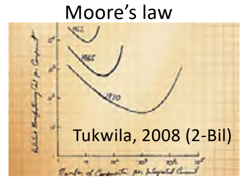
Nanotechnology Historical Milestones

"It would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. . . . Put the atoms down where the chemist says, and so you make the substance." - Richard Feynman, *There's Plenty of Room at the Bottom* (Caltech, APS talk, 1959).

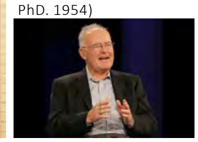
Don Eigler and Erhard Schweizer spelled "IBM" with 35 xenon atoms, 1989. This logo could fit 350 million times in the area at the point of a pin.

"We cannot afford certain types of accidents" - Eric Drexler, *Engines of creation*, 1986, the book where the term "grey goo" was coined.

Moore's law



Gordon Moore, Intel Founder (Caltech, PhD. 1954)



"My budget supports a major new National Nanotechnology Initiative, worth $500 million. More than 40 years ago, Caltech's own Richard Feynman asked, 'What would happen if we could arrange the atoms one by one the way we want them?'" - President Clinton, Caltech (2000).

Precise and intentional manipulation of matter at the atomic scale

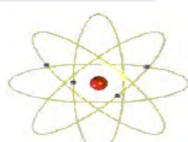
Fundamentos: Microscopia Atomic y Electronica, 2021

5

Erwin Shrödinger (1887-1961)

Schrödinger's Equation: Conceptual Understanding

$$H(R)\psi(R) = E\psi(R)$$



1925

$$\hat{H} = \hat{K} + V$$

$$\hbar = h/2\pi$$

$$\left[-\frac{\hbar}{2m}\nabla^2 + V(R)\right]\psi(R) = E\psi(R)$$

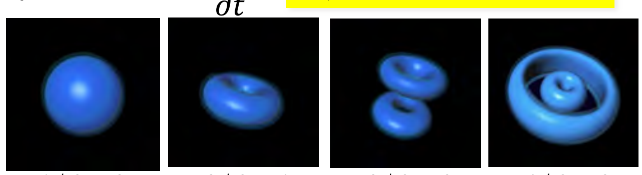
$$-\frac{\hbar}{2m}\nabla^2\psi(R,t) + V(R)\psi(R,t) = i\hbar\frac{\partial\psi(R)}{\partial t}$$

Probability wave function

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

- Bohr's atomic model -> one-dimensional, i.e. one quantum number to describe the distribution of electrons - *size* of the orbit (*n*).
- Schrödinger's model allowed the electron to occupy three-dimensional space (n,l,m).

n: principal (integer): orbit size
l: azimutal (angular momentum): orbit form
m_l: magnetic: orbit orientation
m_s: spin



n=1, *l*=0, *m*=0 | *n*=3, *l*=2, *m*=1 | *n*=3, *l*=2, *m*=2 | *n*=4, *l*=2, *m*=2

6

Andrés Jaramillo-Botero (2018)

6

Ideally

Atoms are made up of interacting nuclei and electrons, with a

- Total classical Energy: $E = K_e + K_n + V_{ee}(r) + V_{en}(r,R) + V_{nn}(R)$
- Total Hamiltonian: $\hat{H} = \hat{K}_e + \hat{K}_n + V_{ee}(r) + V_{en}(r,R) + V_{nn}(R)$

$$\hat{H} = -\frac{\hbar}{2m}\sum_i \nabla_i^2 - \frac{\hbar}{2M_n}\sum_n \nabla_n^2 + \frac{1}{2}\sum_{ij}\frac{e^2}{|r_i - r_j|} - \sum_{ni}\frac{Z_n e^2}{|R_n - r_i|} + \frac{1}{2}\sum_{nm}\frac{Z_n Z_m e^2}{|R_n - R_m|}$$

Kinetic Energy — No analytical solution — Potential Energy — Large (cannot neglet)

- where indexes *n*, *m* run on nuclei, *i* and *j* on electrons, R_n and r_i are positions of the nuclei and of the electrons, Z_n the atomic number of nucleus *n*, M_n its mass and *m* the electron mass.

In principle, one should solve a Schrödinger equation for the total wavefunction $\psi(R_n, r_i)$ and then everything about the system should be known.

$$H(R,r)\psi(R,r) = E\psi(R,r)$$

7 Andrés Jaramillo-Botero (2018)

7

Approximations to Schrödinger's Equation

1. **Born-Oppenheimer Approximation** (1923)
   - aka **Adiabatic Approximation**
   - **Concept:**
     - Nuclei are much heavier than electrons (H),
     - Nuclei move in a much slower time scale than electrons.
   - **Classical interpretation:**
     - Nuclei interacting with electrons with spring-like forces leads to higher frequency oscillations of the light e's
   - **Quantum interpretation:**
     - For the time-dependent Schrödinger's equation we fix the nuclear geometry (at a particular time) and solve the e part of the total wavefunction

$$\frac{M_{nuc}}{m_{el}} \approx 1{,}840$$

$$\frac{\omega_{el}}{\omega_{nuc}} >> 1$$

8 Andrés Jaramillo-Botero (2018)

8

Further Approximations to Schrödinger's Equation that Lead to MM/MD

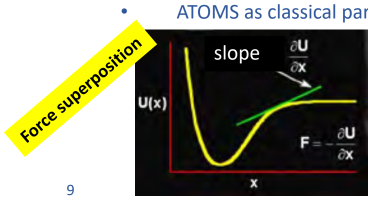
2. Nuclei moving as classical particles

- Since there are no explicit electronic contributions in the nuclear Schrödinger equation, it can be replaced by a Newtonian EOM
  - Introduces the idea of a **Potential Energy Surface (PES)**

$$[K_n(R) + V_{nn}(R) + E^{el}_{eig}(R)]\psi^n(R) = E\psi^n(R) \longrightarrow M\frac{\partial^2 R}{\partial t^2} = F \longleftarrow F = -\frac{\partial}{\partial R}\left[V_{nn}(R) + E^{el}_{eig}(R)\right]$$

3. Approximate PES with analytical potentials

- Avoid solving a Schrödinger equation altogether, and
- ATOMS as classical particles (w/implicit electrons) moving on analytical **PES**



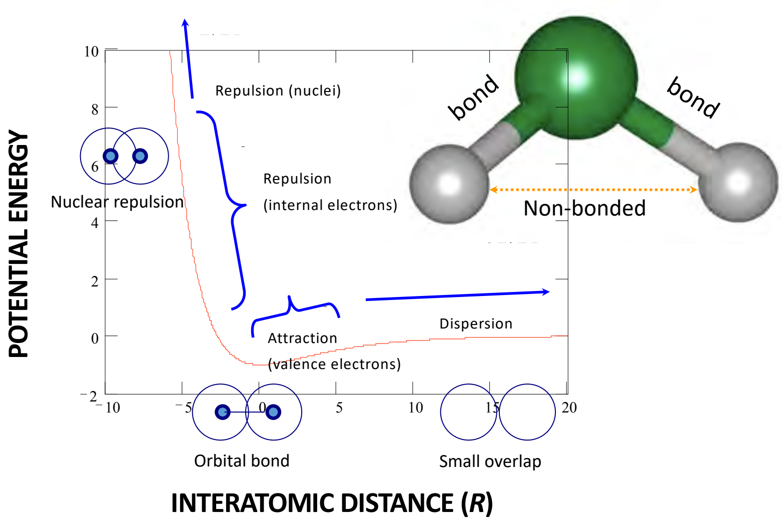
GROUND STATE

E as a function of nuclear positions only.

9 Andrés Jaramillo-Botero (2018)

9

MM/MD (Classical): PES vs. Distance



10 Andrés Jaramillo-Botero (2018)

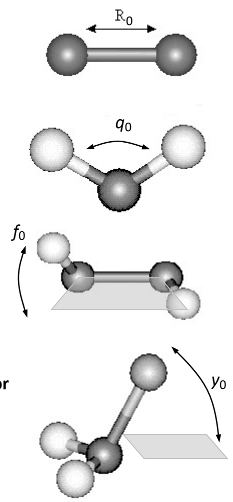
10

Bonded (valence) Interactions

spring-like interactions

"hard" DOF: Bond stretch, Bond Angle

Account (along with non-bond) for variations in structure and relative E: Torsion



Description	Illustration	Typical Expressions: Energy (Potential)	Typical Expressions: Forces
Bond stretch		$U_r = \frac{1}{2}k_r(R-R_0)^2$	$-\frac{\partial U_r}{\partial R} = -k_r(R-R_0)$
Bond Angle		$U_\theta = \frac{1}{2}k_\theta(\cos\theta - \cos\theta_0)^2$	$-\frac{\partial U_\theta}{\partial \theta} = k_\theta(\cos\theta - \cos\theta_0)\sin\theta$
Torsion		$U_\phi = k_\phi[\cos(n\phi - d)+1]$	$-\frac{\partial U_\phi}{\partial \phi} = k_\phi dn \sin(n\phi)$
Inversion or Improper Torsion		$U_\psi = \frac{1}{2}k_\psi(\cos\psi - \cos\psi_0)^2$	$-\frac{\partial U_\psi}{\partial \psi} = k_\psi(\cos\psi - \cos\psi_0)\sin\psi$

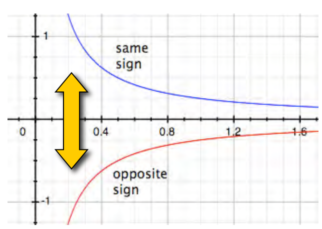
Subindex 0 indicates rest value / Kx: Force constant (kcal/mol A²) / $K_{t,n}$: Rotational barrier (kcal/mol) / n: periodicity / d: phase factor

Others: Cross-terms

11

Non-bond distance-dependent Interactions

90-95%



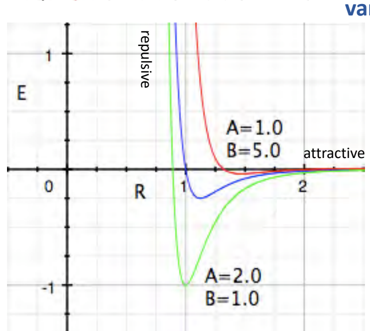
Electrostatic Interactions

Cut-offs and PBC

$$U_{Coulomb} = C_0 \sum_{i>j} \frac{Q_i Q_j}{\varepsilon R_{ij}} S(R_{ij}, R_{on}, R_{off})$$

A function of charges, interatomic distance, and molecular dielectric (attenuates environment). Partial atomic charges from QM

van der Waals Interactions



$$U_{vdW} = \sum_{\substack{R_{ij} > Rcut \\ [excl(1-2,1-3)]}} \hat{U}_{vdW}(R) S(R_{ij}, R_{on}, R_{off})$$

Typical vdW potential:
- Lennard-Jones 12-6

$$\hat{U}_{vdW} = \sum_i \sum_j \frac{-A_{ij}}{R_{ij}^6} + \frac{B_{ij}}{R_{ij}^{12}}$$

- "A" -> degree of **"stickiness"** of the van der Waals attraction (obtained from polarizability measurements or from QM) and
- "B" -> degree of **"hardness"** of the atoms (crystallographic data to observe contact distances)

Co=Conversion factor (332.0637Kcal/mol) / ε=dielectric constant

12 Andrés Jaramillo-Botero (2018)

12

Nanotechnology Definition

Nanotechnology is application agnostic

Not "nano by accident"

"The purposeful engineering of matter at scales of less than 100 nanometers to achieve size-dependent properties and functions

Matthew Nordan, Lux Research, 2005.

Smaller than we've ever manufactured

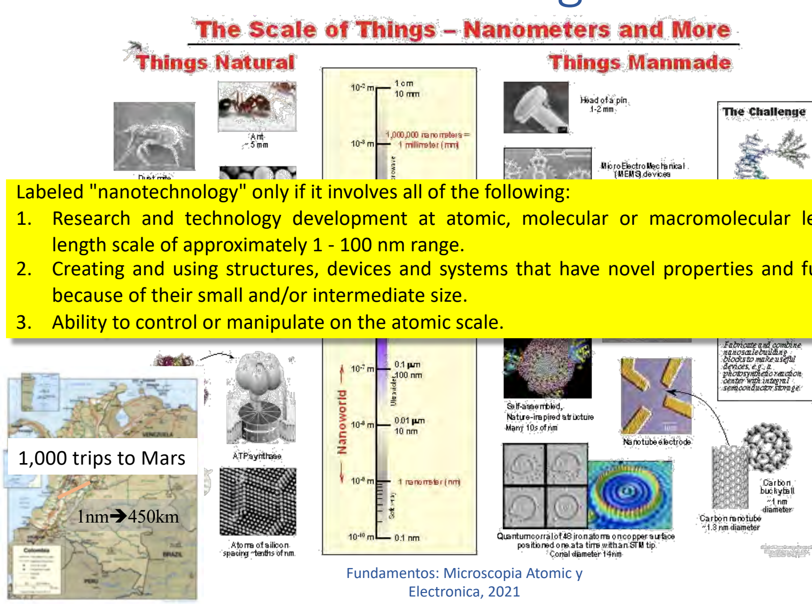
Not just "small;" "small and different"

- AKA: **Molecular Manufacturing**
- **Shift in paradigm:** Bottom-up vs Top-down
- **1 nm** = 1 billionth of a meter!

Fundamentos: Microscopia Atomic y Electronica, 2021

13

www.nano.gov



Labeled "nanotechnology" only if it involves all of the following:

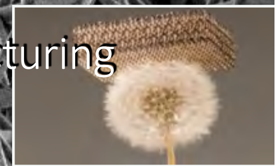
1. Research and technology development at atomic, molecular or macromolecular levels, in length scale of approximately 1 - 100 nm range.
2. Creating and using structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.
3. Ability to control or manipulate on the atomic scale.

Fundamentos: Microscopia Atomic y Electronica, 2021

16

Courtesy of Julia Greer, Caltech

Towards molecular manufacturing



- Atoms are the building blocks of matter, they live in the nanoscale
- Nano: dominated by electromagnetic forces, quantum effects, SA/V, and Brownian
- Atomic composition+structure=material properties (at every scale)
- Power to control material properties at any scale
- Nanoscience is multidisciplinary (Engineering, Physics, Chemistry, Math, etc.)
- Will impact the world as we know it, more than any other field, if we manage:

Arbitrary control of atomic position and composition in 3D, via self-assembly and self-replication

Key: assemble like nature, i.e. **bottom-up**

Acc.V Magn WD 10 µm
5.00 kV 2048x 4.8

What makes the nanoscale special?

Jaramillo-Botero et al, Nanomedicine: A Systems Engineering Approach, Pan Stanford Publishing (World Scientific), Nov. 2008.

1. **Interfaces**
2. **Quantum effects**
3. **Thermal fluctuations**
4. **Discreteness of matter**

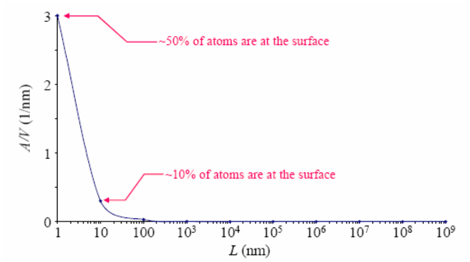
These:

- Can lead to differences between nanosystems and bulk
- Can be exploited to generate whole new devices and phenomena
- Can pose challenges that require novel solutions

Many material properties, including melting point, fluorescence, electrical conductivity, magnetic permeability, and chemical reactivity change as a function of particle size

What makes the nanoscale special: interfaces

Consider surface area to volume ratio as a function of size entity

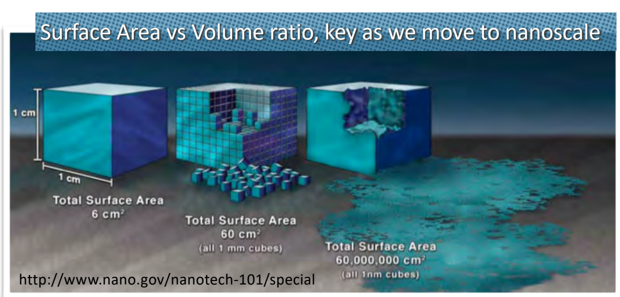


Challenges and benefits of nanoscale come from interfaces!

What makes the nanoscale special: Surface area (SA) to volume (V)

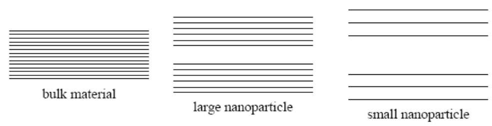
Jaramillo-Botero et al, Nanomedicine: A Systems Engineering Approach, Pan Stanford Publishing (World Scientific), Nov. 2008.

- A larger SA/V ratio as a function of entity size
  - Assume cube with side *l*, $V=l^3$ and $A=6l^2$ then $A/V=6/l$ increases for small *l*
  - In cells: surface must allow sufficient exchange to support contents, hence ratio limits size (e.g. Eukaryotic cell ~5–100µm)
  - Higher ratio leads to more surface available for reactiongs (e.g. in enzymes)



What makes the nanoscale special: Quantum Effects

- Consider the energy levels of a metal as its size decreases



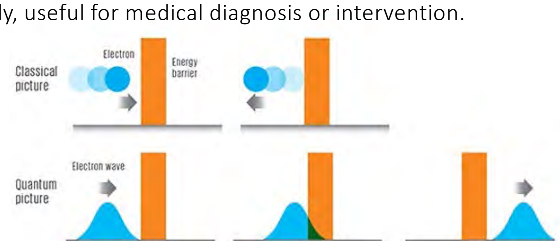
- Heisenberg's Uncertainty Principle: e.g. the more an electron is confined, the greater its momentum range, and vice versa
- Quantum effects can yield a range of exploitable phenomena, e.g.:
  - Nanoscale gold particles selectively accumulate in tumors and the motion of their electrons is confined, which changes its optical response properties, so they can enable both precise imaging and targeted destruction of tumor
  - "Tunability of properties" implies that particle size can be used to fine-tune a material property of interest (e.g., changing fluorescence color in QD)
  - "Electron tunneling" have enabled STMs and flash memories

Fundamentos: Microscopia Atomic y Electronica, 2021

21

What makes the nanoscale special: Quantized energy states at atomic level

- Discrete quantum levels of a nanocluster may be tuned to modulate the electron transport, normally modulated by the pH, ions, and redox centers.
- Important Quantum effects include "electron tunneling" for STM, quantum Hall effect for resistance calibration instruments, spin polarization in MRI.
- Radiation induced processes such as photoisomerization in vision and photosynthesis in plants depend on quantum yield, which depends in turn on molecular structure.
- Novel optical and magnetic properties for nanometer scale devices potentially, useful for medical diagnosis or intervention.

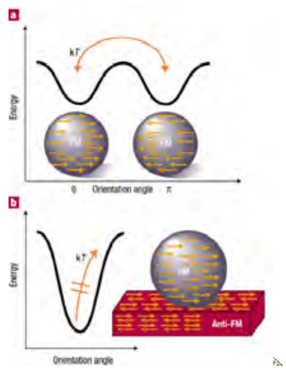


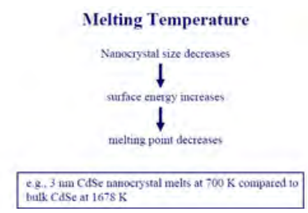
Fundamentos: Microscopia Atomic y Electronica, 2021

22

What makes the nanoscale special: Thermal fluctuations

Thermal fluctuations can be commensurate with size of nano-system





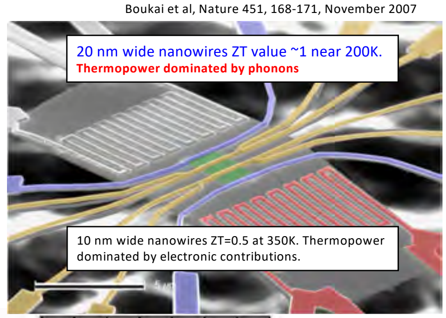
"For very small ferromagnetic (FM) particles the magnetic anisotropy energy (responsible for keeping the magnetization oriented in certain directions) is comparable to the thermal energy (kT). When this happens, the particles become *superparamagnetic*; as thermal fluctuations randomly flip the magnetization direction between parallel and antiparallel orientations. b, When the ferromagnetic nanoparticle is placed close to an antiferromagnetic (Anti-FM) surface the exchange bias interaction at the FM/Anti-FM interface provides additional anisotropy energy, which stabilizes the magnetization in one direction and prevents superparamagnetism."

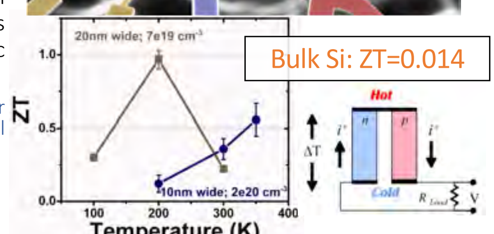
Eisenmenger and Schuller, Nature Materials, 2003

What makes the nanoscale special: Thermal fluctuations

Boukai et al, Nature 451, 168-171, November 2007

- Magnetic anisotropy energy comparable to thermal energy, so thermal noise may alter electric or magnetic dipoles of macromolecules.
- Affect positional variance and conformations (shape and structure) of molecular structures.
- Thermal transport properties depend on the number of interfaces which can dampen phonon vibrations without altering electronic conduction.
  - Such effects could be used for thermal regulation through novel thermoelectric devices.



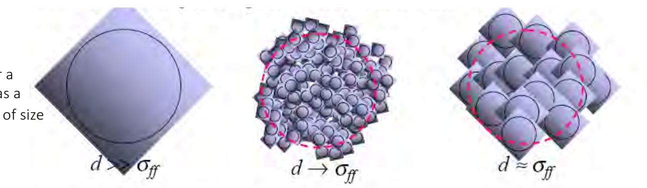


What makes the nanoscale special: surface Discreteness

Once the size of an entity approaches that of its building blocks:

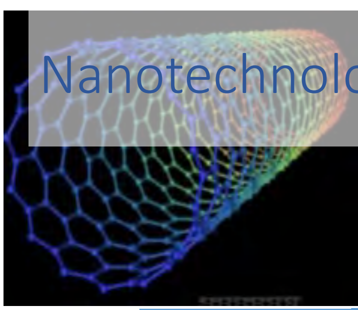
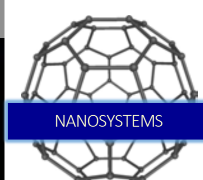
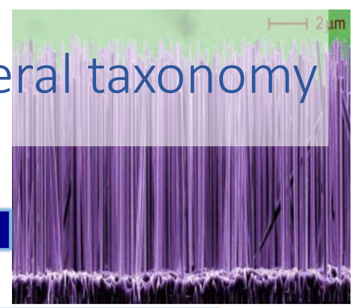
- Surfaces can no longer be assumed 'smooth' – they are ill-defined
  - long alkanes used as lubricants in macrosystems, but act as dirt in nm scale
  - vdW forces in conventional gears taken to the nano hinder normal operation

Consider a droplet as a function of size



- Thermal fluctuations affect shape and structure
- Obscures bulk concepts as surface tension, dielectric constant, pH

Nanotechnology: general taxonomy

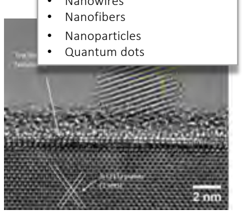
NANOSYSTEMS

Nanostructures
- Fullerenes
- Nanotubes
- Nanowires
- Nanofibers
- Nanoparticles
- Quantum dots

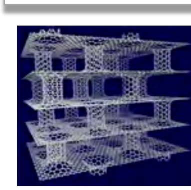
Nanostructured Materials
- Nano grains
- Nano crystalline materials
- Nano compounds

Nano devices
- Electronic
- NEMS
- Bio-devices(lab on chip)
- Bio-sensors
- Drug Deliver Systems
- Nano-machines

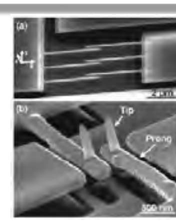
Nanotools
- Fabrication
- Analysis
- Modeling



Madhukar, silicon QDs, USC

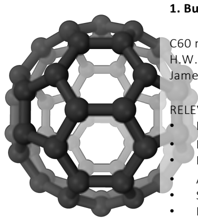


Dimitrakakis et al, Pillared graphene, DOI: 10.1117/2.1200902.1451



Meyer et al, Nanotweezers, Appl. Phys. Lett. 83, 2420 (2003).

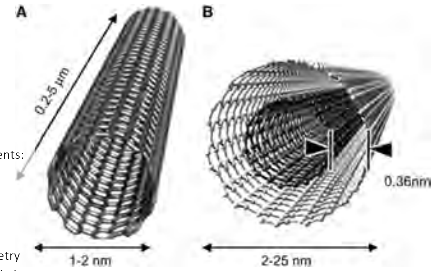
Nanostructures: C based



1. Buckyballs (fullerene)

C60 molecule (1985) by R.E. Smalley, R.F. Curl and H.W. Kroto (Nobel Prize 1996) with graduate students: James Heath (now at Caltech) and Sean O'Brien

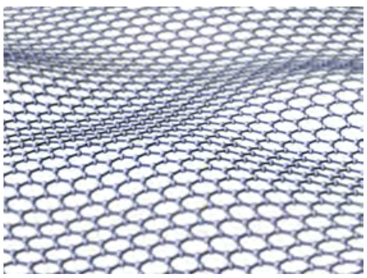
RELEVANCE:
- New form of carbon
- High mechanical strength (very stable)
- Exposed surface reacts without loosing geometry
- Atoms and small molecules can be contained in it
- Soluble in aromatics, insoluble in water
- Dopable



2 Carbon Nanotubes

Single sheet of graphite rolled up (1991) by Sumio Iijima of NEC

RELEVANCE:
- Another new form of carbon
- High mechanical strength (up to 25GPa P),
- High thermal conductivity,
- Metallic or semiconductor transport properties,
- Superhydrophobic surface
- High length-to-diameter ratios achievable 132,000,000:1



3. Graphene

Single planar sheet of sp2-bonded carbon atoms, by Andre Geim and Konstantin Novoselov (2004) – Nobel prize 2010; 2D counterpart of graphite.

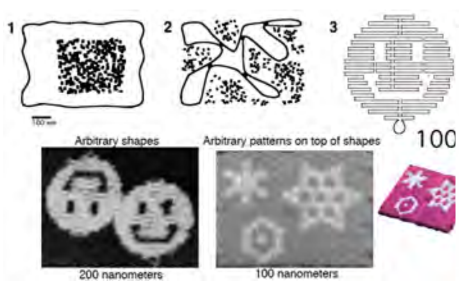
RELEVANCE:
- 100 times stronger than the strongest steel
- Conducts heat and electricity efficiently (zero-gap semiconductor, high electron mobility 15000 $cm^2 \cdot V^{-1} \cdot s^{-1}$)
- Optically transparent
- Non-linear diamagnetism (can be levitated by Nd-Fe-B magnets)

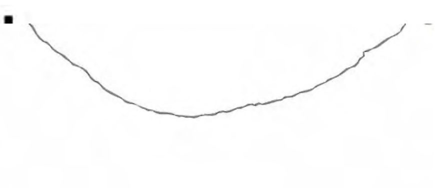
27

Nanostructures: DNA scaffolds via DNA-Origami < 30nm

- Features <100 nm; 200 pixel patterns; 6 nm resolution,
- 100 billions per drop, 90% yield
- Lots of different DNA strands (expensive)

Any form with 250 base sequences and a virus (genome)





- Given a computer design form
- Generate 250 short sequences of DNA (~32 letters)
- "Express" seuqences with a DNA synthesizes
- Mix in Mg2+ solution and add viral strand

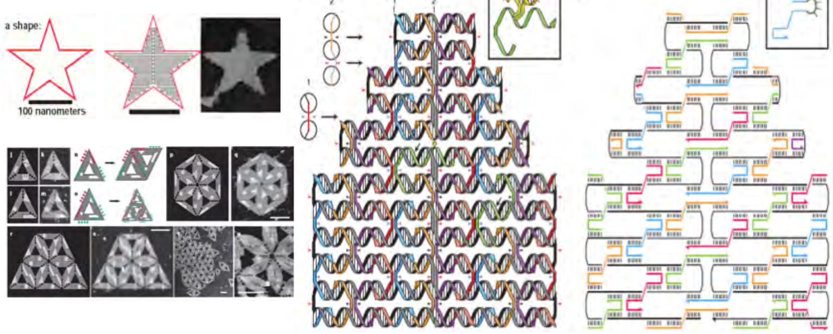
Nano Lett., **12** (3): 1129-1135 DOI: 10.1021/nl201818u (**2012**)

Paul Rothemund, Caltech

28

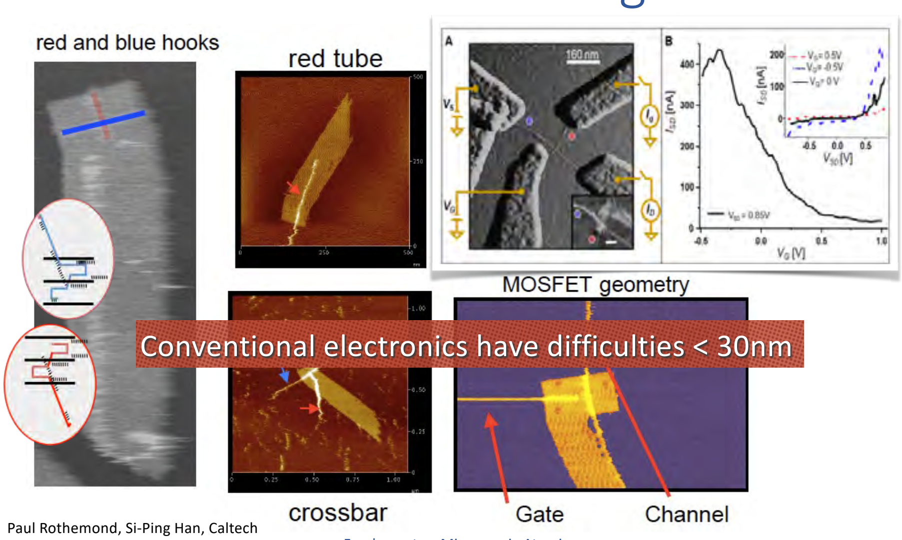
Nanoestructures: via DNA-Origami

Paul Rothemund, Caltech



29

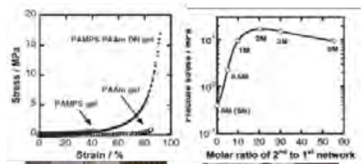
Nanostructures: Self-assembly of FETs with DNA-Origami

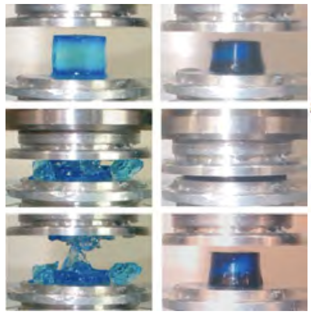


Paul Rothemond, Si-Ping Han, Caltech

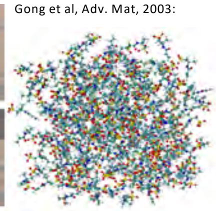
30

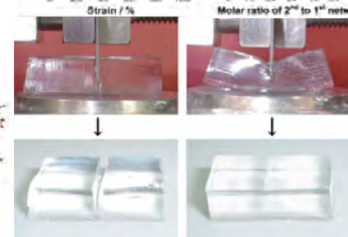
Nanostructures: 2 Polymer Nets for Cartilage Scaffolding





Gong et al, Adv. Mat, 2003:



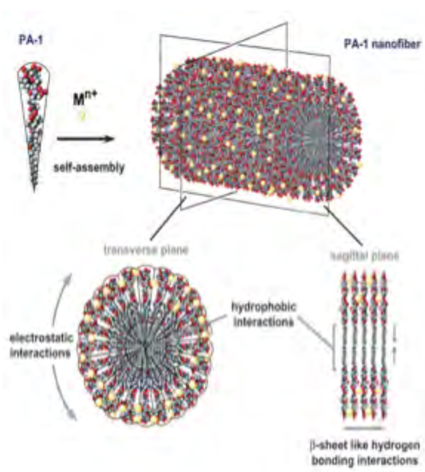


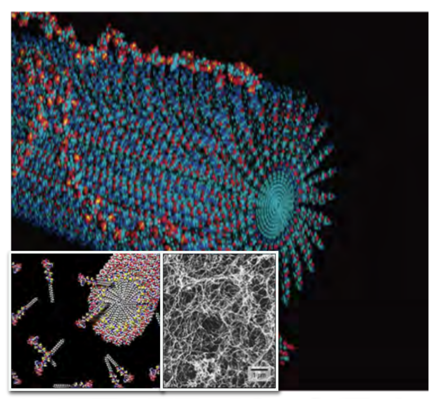
1st hard and brittle (PAMPS-.1-4) + 2nd soft and ductile (PAAm-2-0.1) = 1+2 hard not brittle, ductile not soft

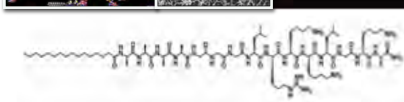
Origin of high mechanical strength in polymer double network hydrogels
- Molar ratio of the 2nd net to the 1st about 10x
- Covalent crosslinking density ratio of the 1st net higher than for 2nd
- Control of internetwork covalent bonding

Jaramillo-Botero et al, J. of Computational and Theoretical Nanoscience,, 7, 1238-1256 (2010)

"Intelligent" Amphiphilic Nano-Peptides for ECM

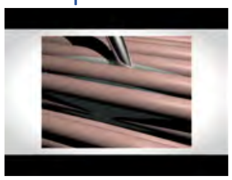






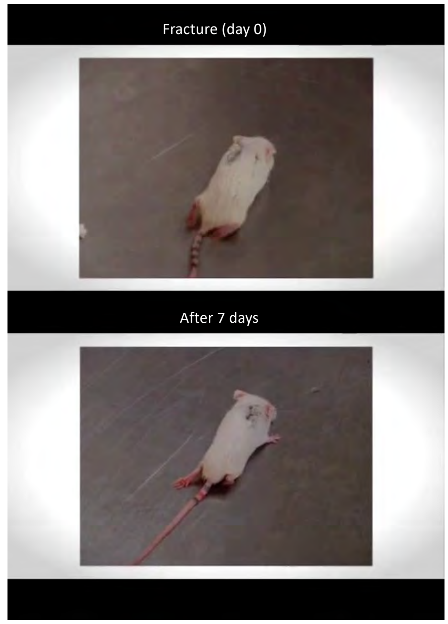
Samuel Stupp, NW

Fracture and recovery from spinal cord injury using Amphiphilic Nano-Peptides



- Nano-peptide with IKVAV (neurite growth)
- Nanofiber matrix with progenitor cells (neurons)
- Growth of reactive astrocites suppressed (glial scar)

Samuel Stupp, NW

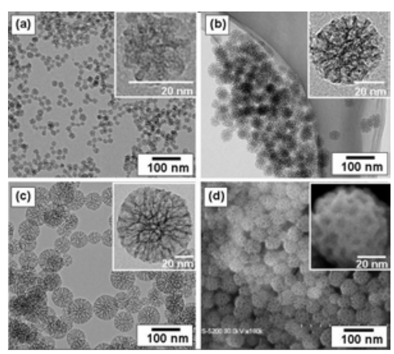


Nanoparticles

Material properties change as their size approaches the nanoscale, as the percentage of atoms at the surface is commensurate with the number of atoms in the material

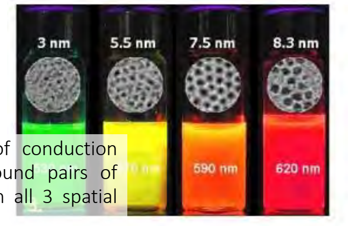
- Particles with size < 100nm (mostly inorganic)
- Bridge bulk materials and atomic/molecular structures
- Behave as a whole unit with respect to transport and properties
- Large surface area to volume ratio

RELEVANCE
- Variety of applications (optical, electronic)
- Quantum confinement in semicond. particles
- Surface plasmon resonance in metal particles
- Superparamagnetism in magnetic materials



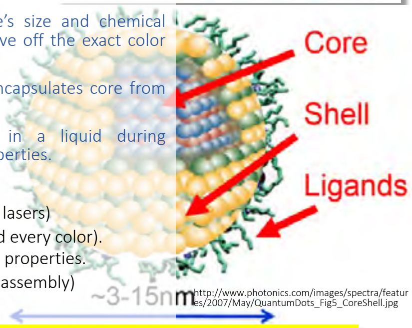
TEM images of mesoporous silica nanoparticles with mean outer diameter: a) 20nm, b) 45nm, and c) 80nm. d) is a SEM image of b). The insets are a high magnification of mesoporous silica particle. Source: Wikipedia

Nanoparticles: Quantum dots (QD)



Semiconductor nanostructure that confines motion of conduction band electrons, valence band holes, or excitons (bound pairs of conduction band electrons and valence band holes) in all 3 spatial directions

- Core material emits pure, bright colors. Core's size and chemical makeup tuned on an atom-by-atom basis to give off the exact color light needed.
- Shell coating (different material) protects or encapsulates core from moisture and oxygen.
- Ligands, ensure that QD can be printed in a liquid during manufacturing, and play a role in electronic properties.



RELEVANCE

- Can self-assemble into periodic arrays (heterostructure lasers)
- QD can emit any wavelength of light, from UV to IR (and every color).
- Shell in QD enables fine tuning emitted color and other properties.
- Ligands can be used to do selective chemistry (e.g. self-assembly)

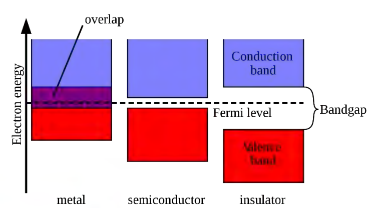
http://www.photonics.com/images/spectra/features/2007/May/QuantumDots_Fig5_CoreShell.jpg

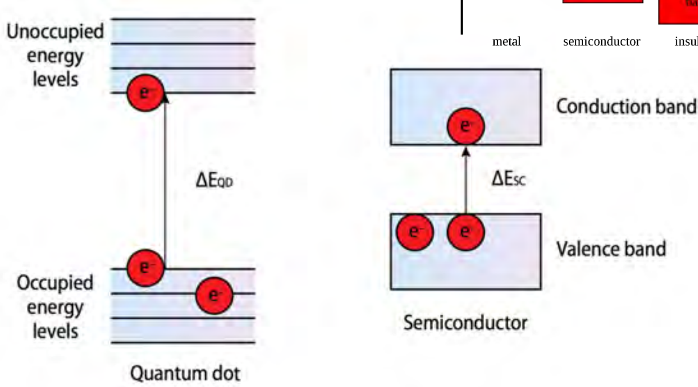
The smaller the quantum dot, the larger the energy gap between the energy levels and hence the higher the frequency of light emitted

Fundamentos: Microscopia Atomic y Electronica, 2021

35

Electronic band structures





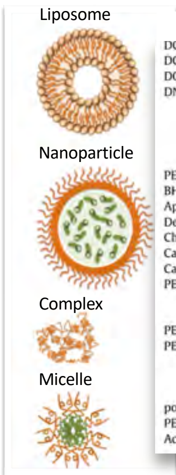
The smaller the quantum dot, the larger the energy gap between the energy levels and hence the higher the frequency of light emitted

Fundamentos: Microscopia Atomic y Electronica, 2021

36

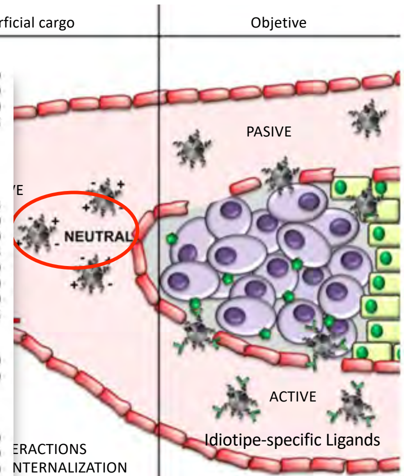
Nanoparticles: for DDSs

TIPe	Size	Superficial cargo	Objetive



Type	Composition	% encapsulation
Liposome	DC–Chol, DOPE, DSPE–PEG, F'ab Her2	80
	DC-6–14, POPC, Chol, DOPE, DSPE–PEG	90
	DOTAP, DOPE, Chol, PEG–C16Ceramide	90
	DNA, protamine, DOTAP, Chol, DSPE–PEG	95
Nanoparticle	PEG, lecithin, triglycerides, DOTAP, DOPE	65
	BHEM–Chol, mPEG–PLA	90
	Apolipoprotein A-I, Chol, CE, PC, Oligolysine	>90
	Dextran thiol, Dextran stearylamine, PEG-thiol	95
	Chitosan, Plurol, Ammonium nitrate, PIBCA	90
	CaP, DOTAP, Chol and DSPE–PEG,	40
	CaP, PEG–Pasp(DET–Aco)	90
	PEI, Tripalmitin, DSPE–PEG–folate, Chol, Lecithin	85
Complex	PEI, Glycol chitosan polymer	100
	PEI, HSA	100
Micelle	poly(DMAEMA), mAB-SA	100
	PEG-SS-Pasp (DET)	100
	Acetal-PEO-b-PCCL	>90

Biomaterials 34 (2013) 6429e6443



NATURAL RENAL CLEARANCE

Safe and Selective Delivery (size, stability, ...)

Simulations predicted Swell (12-180%) when pH decreases

Drug encapsulation/release using dendrimers

- 180% Difference in R_G Muthukumar et al., Macromolecules 31 5892 1998
- 100% Difference in R_G Baker Jr. et al., Macromolecules 35 4510 2002
- 12% Difference in R_G Goddard III et al., J. Phys. Chem. B 110 25628 2006
- 50% Difference in R_G Wagner et al., J. Poly. Sci. B: Poly. Phys. 44 3062 2006

Dendrimer: ultrasoft colloid or structured polymer

Questions:

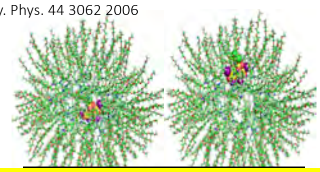
- Drug encapsulation (interior or exterior binding sites?)
- Drug release (pH effect? Protein?)

Systems:

- Dendrimer-drug (PAMAM-MPA)
- Dendrimer-drug-protein(PAMAM-MPA-HSA)
- Dendrimer-protein (PAMAM-HSA)
- Dendrimer (PAMAM)

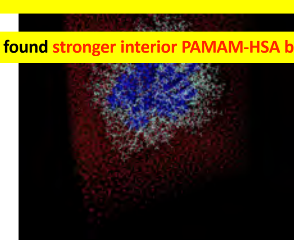
Approaches:

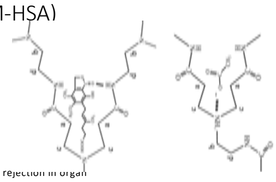
- Experiment (NMR)
- Theory (MM/MD)



Interior PAMAM-MPA bindings through hydrophobic/H-bonding

NMR-MD studies found stronger interior PAMAM-HSA bindings





Mycophenolic acid (MPA): immunosuppressant to prevent rejection in organ transplantationhuman serum albumin (**HSA**)
Poly(amidomaine) (**PAMAM**) dendrimers

Yi Liu, Vyacheslav S. Bryantsev, Mamadou S. Diallo and William A. Goddard III J. Am. Chem. Soc., **2009**, 131 (8), pp 2798–2799

Nanowires

Structures that have a lateral size constrained to tens of nanometers or less, and an unconstrained longitudinal size (ratio of length to width > 1000)

- **Metallic (e.g. Ni, Pt, Au), semiconducting (e.g. Si, GaN), insulating (e.g. SiO2, TiO2)**
- **Molecular NWs: repeating molecular organic (e.g. DNA) or inorganic units**

RELEVANCE

- **New electrical properties (ideal for solar cells and metamaterials, transistors)**
- **New thermoelectrical properties (e.g. cooling semiconductors)**

2 µm

Image source: https://www.cvdequipment.com/parts-services/lab-services/

Fundamentos: Microscopia Atomic y Electronica, 2021

39

Nanofibers

- Fibers with diameters less than 100 nm.
- Can be produced by interfacial polymerization or electrospinning

RELEVANCE

- Low density, large surface area to mass, high pore volume, and tight pore size
- Appropriate for medical, high-tech and aerospace applications, including: antimicrobial wound dressing, bio-chemical detectors, tissue engineering, ballistic shields, capacitors, transistors, DDS, battery separators, energy storage, fuel cells, and IT

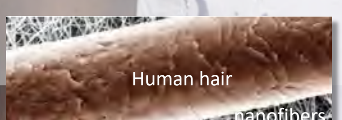
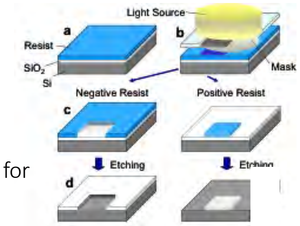


Image source: Silic LLC

Fundamentos: Microscopia Atomic y Electronica, 2021

40

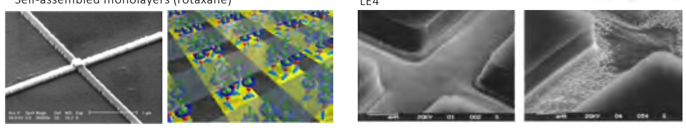
Nanotools



1. Top-Down and Bottom-up Synthesis techniques for nanostructures and nanostructured materials

Self-assembled monolayers (rotaxane)

LE4



APL, 2003 -- Volume 82, Issue 10, pp. 1610-1612

Journal of ELECTRONIC MATERIALS, Vol. 32, No. 7, 2003

2. Characterization and Testing: AFM, Electron scattering, force based techniques, NEMS/MEMS and in-situ testing

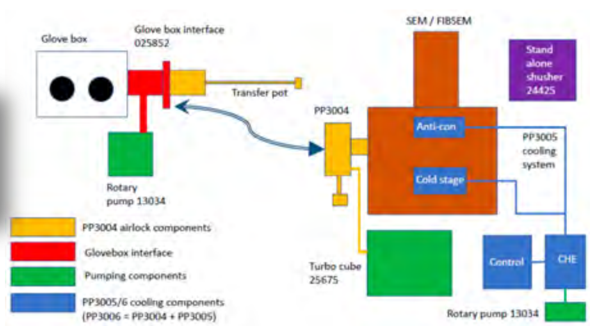
Fundamentos: Microscopia Atomic y Electronica, 2021

3. Modeling and simulation

41

Fundamentos: Microscopia Atomic y Electronica, 2021

Cryo-SEM Sensum-SARS-CoV-2



TESCAN PERFORMANCE IN NANOSPACE

Preparación y transferencia de muestra a SEM

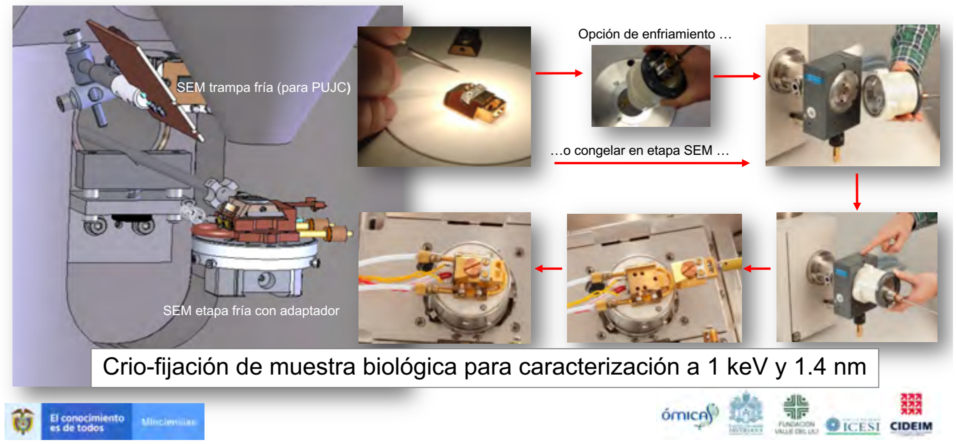
El conocimiento es de todos — Minciencias

ómica — ICESI — CIDEIM

42

Fundamentos: Microscopia Atomic y Electronica, 2021

Cryo-SEM Sensum-SARS-CoV-2

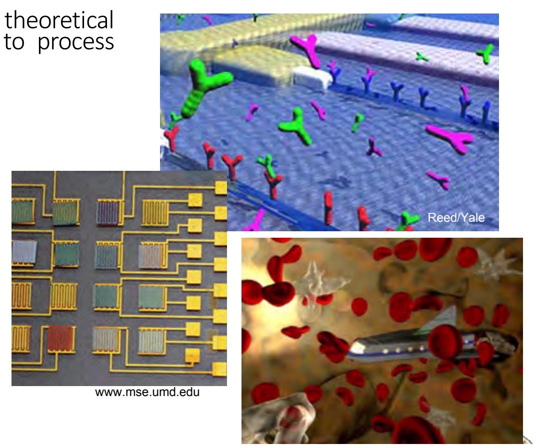


43

Nanodevices

New physics in the numerical, theoretical and experimental techniques to process and study nanomaterials

- Electronic
- NEMS/MEMS
- Biodevices (lab-on-a-chip, biosensors)
- DDS
- Therapeutics
- Data storage
- Catalysis
- Nanoscaled machines

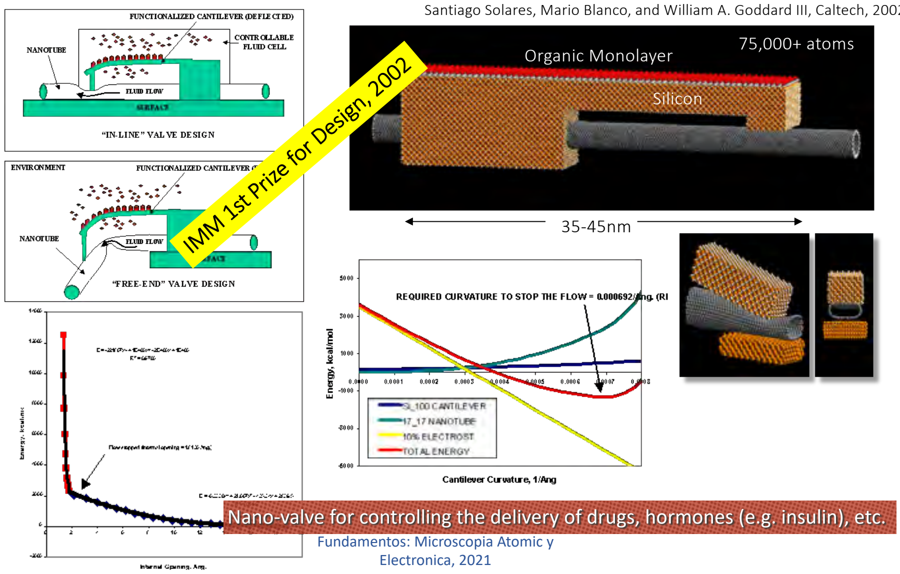


Fundamentos: Microscopia Atomic y Electronica, 2021

44

Nanodevices: Nano mechanical flow valve

Santiago Solares, Mario Blanco, and William A. Goddard III, Caltech, 2002

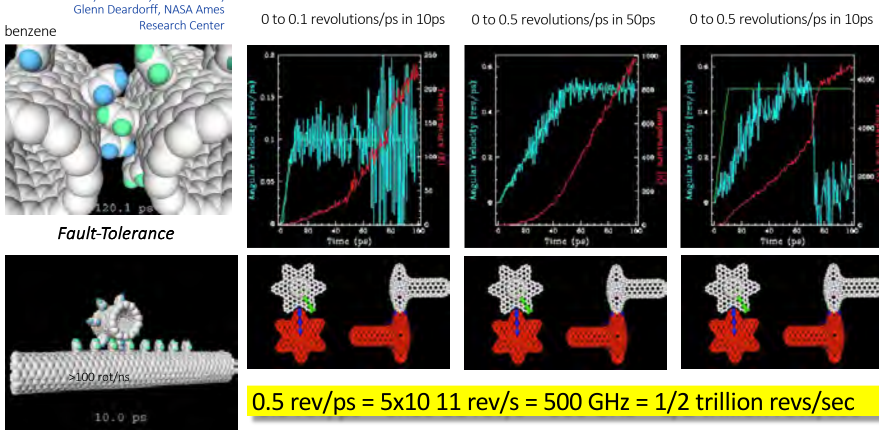


Nano-valve for controlling the delivery of drugs, hormones (e.g. insulin), etc.

Nanodevices: Fullerene and benzene gears (NRL,NASA-Ames)

Jie Han, Al Globus, Richard Jaffe, Glenn Deardorff, NASA Ames Research Center

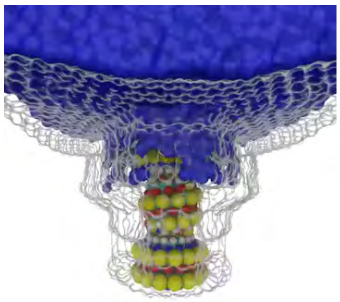
D.H. Robertson, B.I. Dunlap*, & C.T. White*, *Naval Research Laboratory, Washington DC.



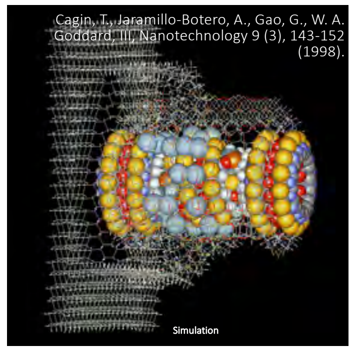
0.5 rev/ps = 5x10 11 rev/s = 500 GHz = 1/2 trillion revs/sec

Nanodevices: “classical” actuators

Control schemes
- Electrionic
- Biological - glucose-oxygen.
- Chemical, radiation, or acoustic

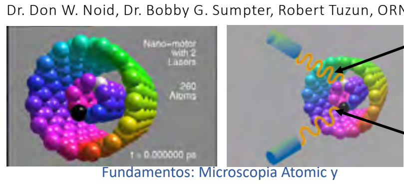


NEON ATOM PUMP



Dr. Don W. Noid, Dr. Bobby G. Sumpter, Robert Tuzun, ORNL

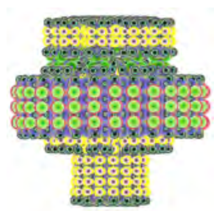
LASER-DRIVEN CNT MOTOR



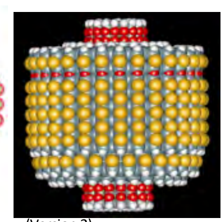
Nanodevices: differential and planetary gears

Cagin, T., Jaramillo-Botero, A., Gao, G., W. A. Goddard, III, Nanotechnology 9 (3), 143-152 (1998).

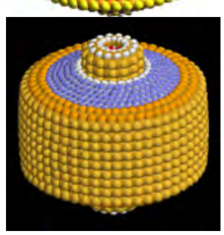
Differential Gear

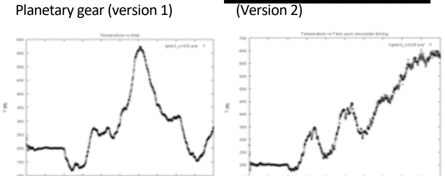


Planetary gear (version 1)



(Version 2)



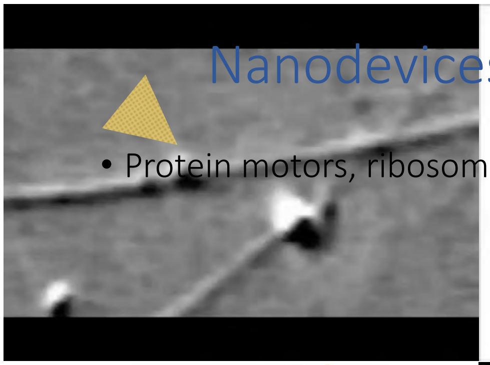


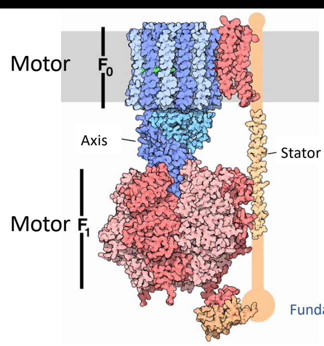
Kinetic Temp / rotation step

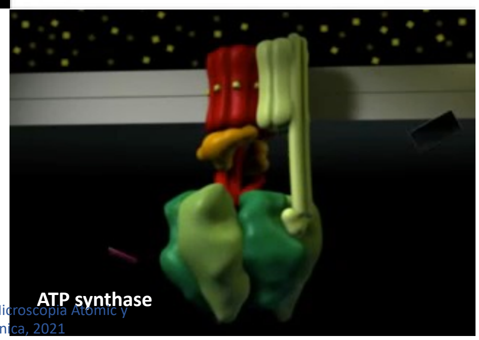
Initial versions not functional due to gear interfaces: high vdW repulsions or gear “slippage”

Nanodevices in nature:

- Protein motors, ribosomes, etc.







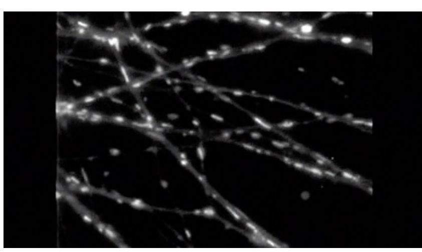
Fundamentos: Microscopia Atomic y Electronica, 2021

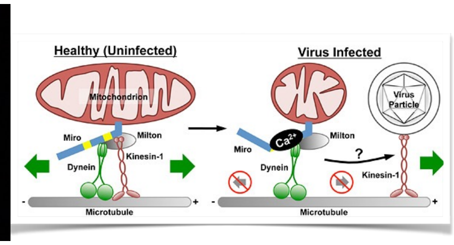
49

Virus kidnaps cell transport system (Kinesin)

- Herpes kidnaps cells mitochondrial system, which regulates the energy supply, communication with other cells, and auto-destruction response to infection

Kramer et al,, Cell Host and Microbe, 2012





Understanding how a viral infection damages neurons could provide new insight into how other illnesses do the same (e.g. Alzheimer)

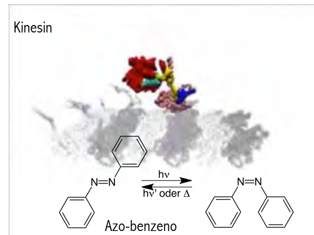
Cell Host & Microbe, Volume 11, Issue 5, 17 May 2012, Pages 420-421

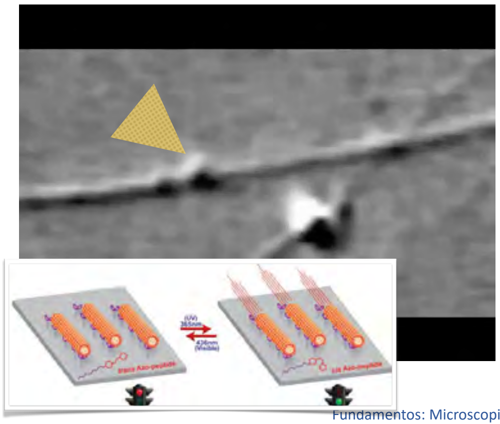
Fundamentos: Microscopia Atomic y Electronica, 2021

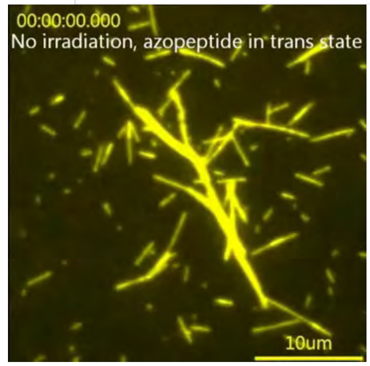
50

Nanodevices: Controlling intra-cellular cargo transport

We could functionalize the cellular machinery to improve fault-tolerance







Chem. Commun., 2013,49, 9935-9937

Nanodevices: 3D positioner - Thermal Noise and Variance

From Statistical Mechanics (and QM)

Thermal noise can be reduced by controlling ***T*** or incrementin stiffness, $\boldsymbol{k_s} \rightarrow f_R = -k_s d$

Example: Transverse stiffness of a cylindrical element of radius r and length L

$$k_S = \frac{3EI}{L^3} = \frac{3\pi r^4 E}{4L^3}$$

$$\sigma^2 = \frac{4L^3 k_B T}{3\pi r^4 E}$$

σ^2 =0.007 nm ← **Less than 1 atomic radii !**

E:	Young's modulus	E:	1012 N/m2
K_S:	Transverse stiffness	K_S:	10 N/m
r/L:	Radius/length	r/L:	8/50nm
k_b:	Boltzmann constant	k_b:	1.38 x 10^{-23} J/K
T:	Temperature	T:	300 K

Diamond parameters used

PDF for x coordinate

$$f_x(x) = \frac{\exp[-V(x)/k_B T]}{\int_{-\infty}^{\infty} \exp[-V(x)/k_B T]\,dx}$$

PE=harmonic oscilator

$$V(x) = \frac{1}{2} k_s x^2$$

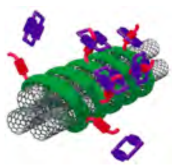
$$f_x(x) = \frac{\exp\left[-k_s x^2 / 2k_B T\right]}{\int_{-\infty}^{\infty} \exp\left[-k_s x^2 / 2k_B T\right] dx} = \frac{\exp\left(-k_s x^2 / 2k_B T\right)}{\sqrt{2\pi}} \sqrt{\frac{k_s}{k_B T}}$$

Posicional Variance

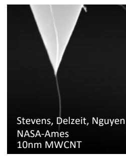
$$\sigma^2 = k_B T / k_S$$

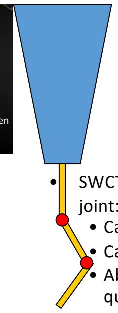
A. Jaramillo-Botero, Encyclopedia of Nanoscience and Nanotechnology, 2004, Marcel Dekker.

Nanodevices: 3D positioner



Sidewall functionalization, to attach oligomer, to CNT (aromatic polymers) [Star, et al, UCLA, Macromolecules 2003]





- **Theoretical Analysis:**
  - Nanomanipulator cannot be treated as Macroscopic counterparts
  - Decoupling and invariance of ABI improves performance (controllability)
  - Simplified dynamics allows larger integration time-steps in rigid-body MD
  - Full decoupling (3DOF): SISO control O(1) parallel dynamic computation
  - Positional variance at the nanoscale can be controlled via stiffness
- **Experimental Feasibility:**
  - Polymeric tendons can improve stiffness of CNTs
  - Same Polymeric element can act as contracting muscle
  - Aromatic polymers can be used to attach muscle/tendons to CNT walls

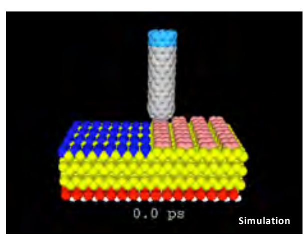
- SWCTN or MWCNT with Azobenzene joint:
  - Can act as a tendon
  - Can act as a muscle (cis configuration)
  - Ab initio calculations to improve quantum efficiency
- Rotational control: modify base oligomers in chain to absorb different frequencies
- CNT Sidewall functionalization of azobenzene with aromatic polymers
- Electrical birefringence to measure rotation (SFSU)
- Other apps: electronic transport properties affected (armchair), high resolution AFM …

Fundamentos: Microscopia Atomic y Electronica, 2021

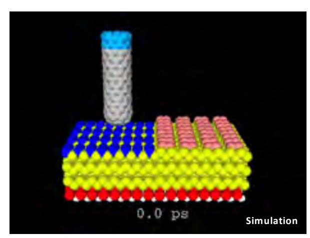
53

Nanodevices: nanoindentation/etching

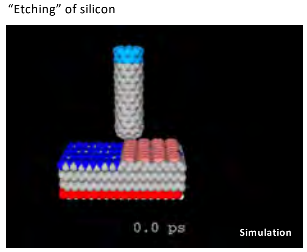
Fedor Dzegilenko, Deepak Srivastava, and Glenn Deardoff, NASA AMES

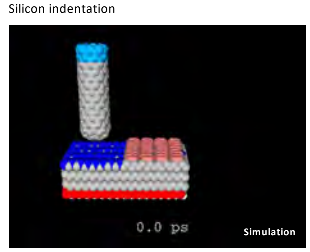


"Etching" of silicon



Silicon indentation

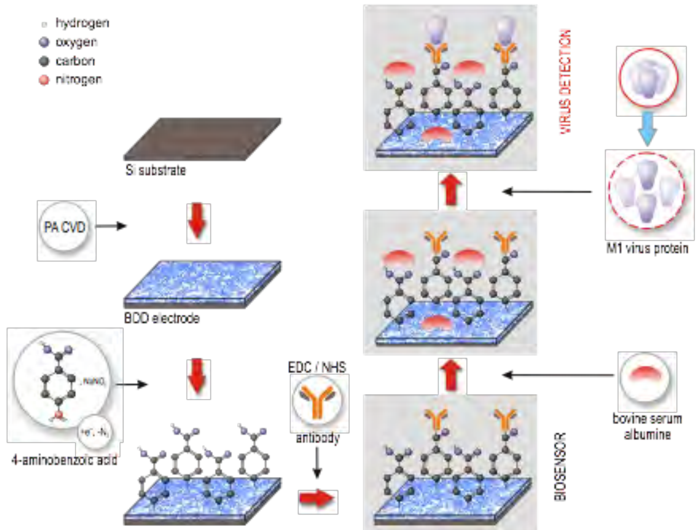




Fundamentos: Microscopia Atomic y Electronica, 2021

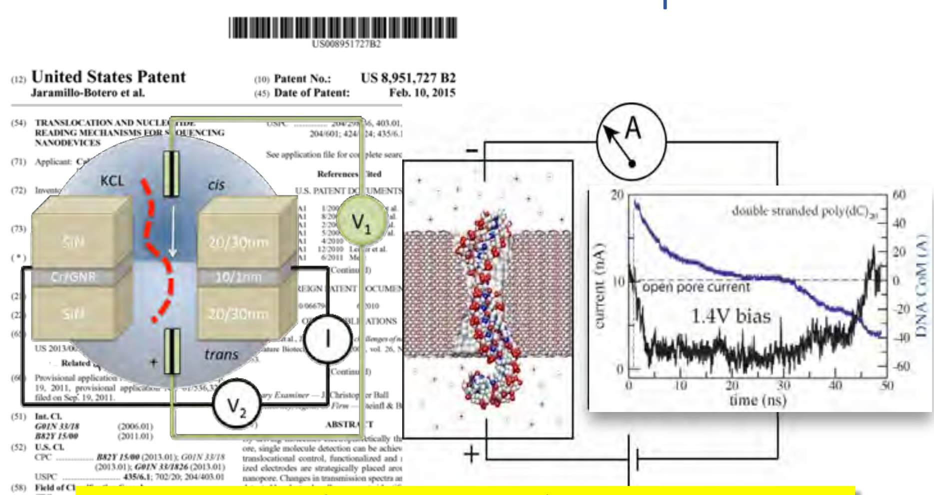
54

Nanodevices: molecular sensors

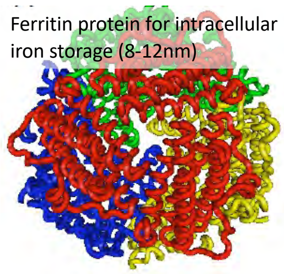


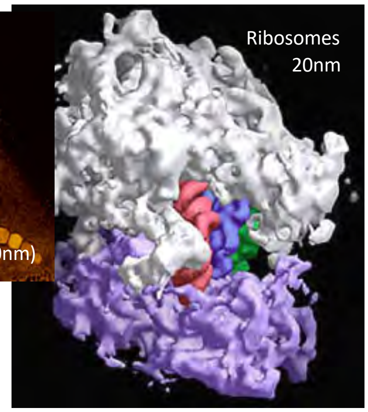
D. Nidzworski[1*#], K. Siuzdak[2*], P. Niedziałkowski[3#], R. Bogdanowicz[4], M. Sobaszek[4], J. Ryl[5], P. Weiher[1], M. Sawczak[2], E. Wnuk[3], W.A. Goddard[6], A. Jaramillo-Botero[6] and T. Ossowski[3]

Nanodevices: 4^G DNA sequencers

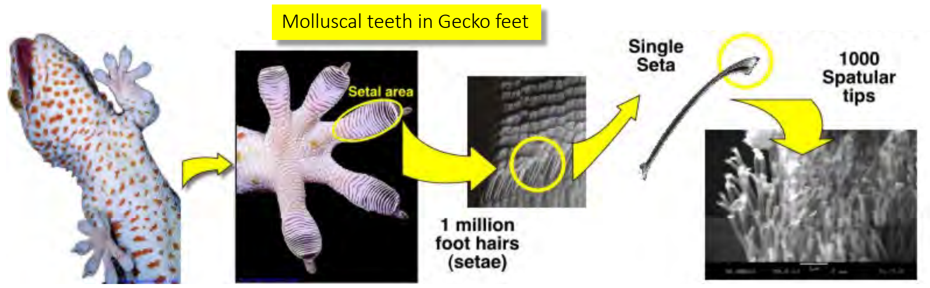


- Read unmarked DNA/RNA at 1K—1M bases/sec (100 - 1M parallel readers)
- Personalized Humane Genomes in <2 hours and <US$1000





Nanostructures and devices in nature



57

Microscopía atómica y electrónica: aplicaciones en nano mecánica

Jhonattan de la Roche, Investigador postdoctoral proyecto 2: Nanosensores

Capacitación AFM

1

CONTENIDO

Módulo 1

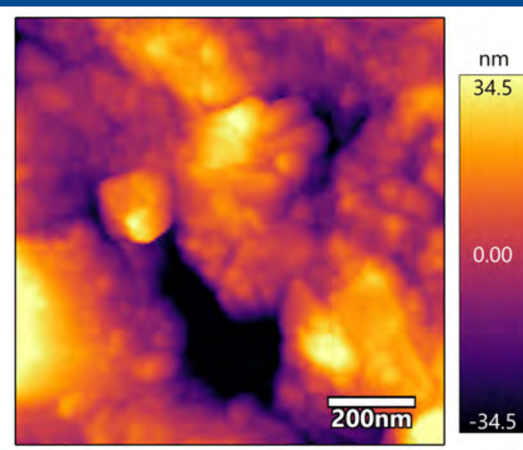
- AFM: Principios básicos y Modo contacto
- Modo no contacto: Principios básicos
- Componentes del equipo
- Cuidados del equipo

Módulo 2

- SEM: Principios básicos
- Componentes del equipo
- Cuidados del equipo

Módulo 3

- Demostración AFM – Modo contacto y medida de fuerza
- Demostración SEM – Muestras de oro y grafeno

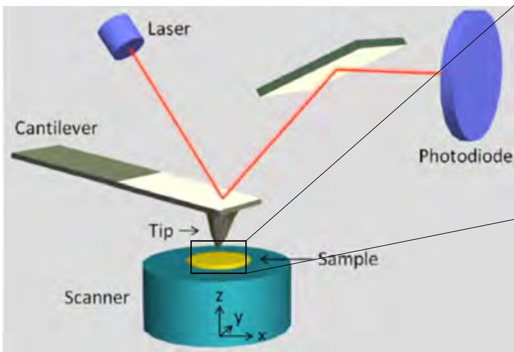


Capacitación AFM

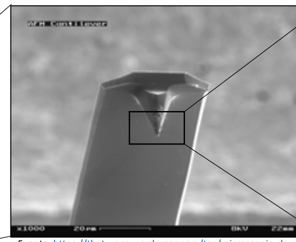
2

AFM: PRINCIPIOS BÁSICOS Y MODO CONTACTO

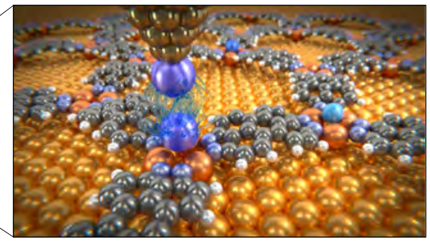
La técnica AFM nació a partir del desarrollo de la microscopía de efecto túnel (STM) [1] → Gerd Binnig y Heinrich Rohrer premio Nobel en 1986 [1] → 1986: Nacimiento del AFM por Binnig, Quate, y Gerber[1,2]



Fuente: G. Zeng, Gong, et al. Atomic Force Microscopy Investigations into Biology-From Cell to Protein (2012)



Fuente: https://thetuzaro.wordpress.com/tag/microscopio-de-fuerza-atomica/



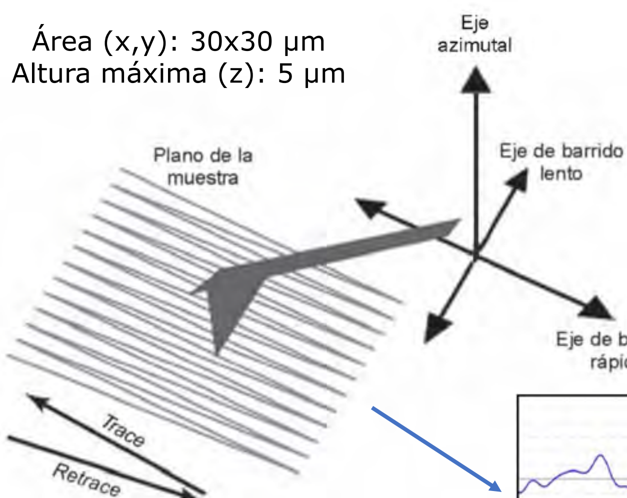
Fuente: https://analyticalscience.wiley.com/do/10.1002/imaging.5540/full/

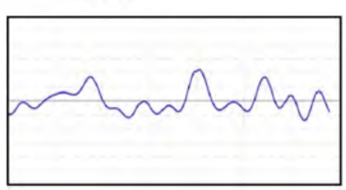
Van der Waals, fuerzas capilares, interacciones químicas, fuerzas electrostáticas, fuerzas magnéticas, fuerzas de solvatación, etc.

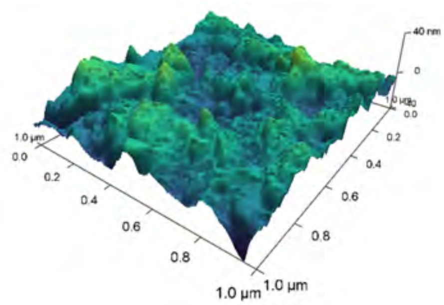
1. *Ron Blonder et. al, Journal of Chemical Education 87 (2010), 1290*
2. *G. Binnig et. al, Phys. Rev. Letters 56, 1(986), p. 930.*

¿COMO MIDE EL AFM?

Área (x,y): 30x30 μm
Altura máxima (z): 5 μm



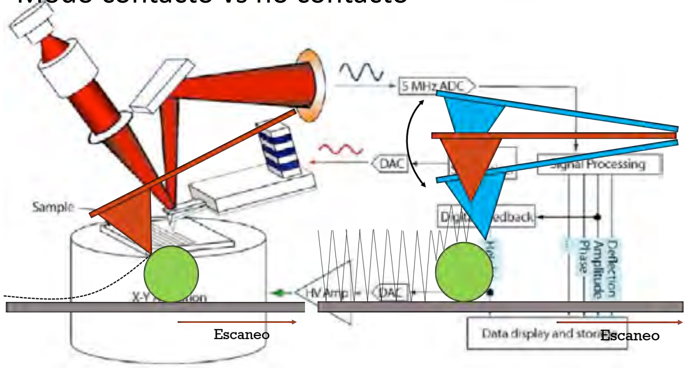




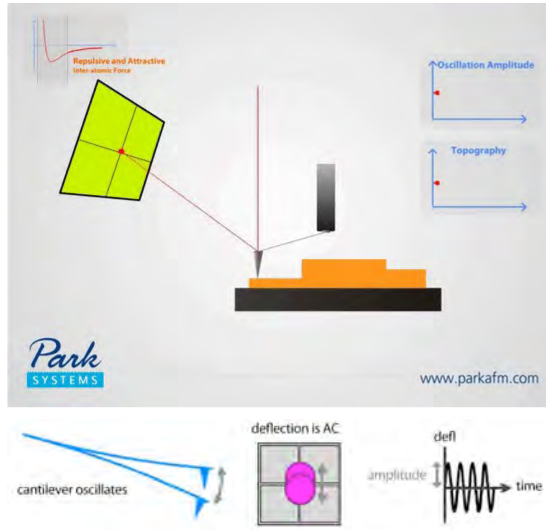
$\sum$

MODO NO CONTACTO: PRINCIPIOS BÁSICOS

Esquema
Modo contacto vs no contacto



Fuente: AR Applications guide (2018)

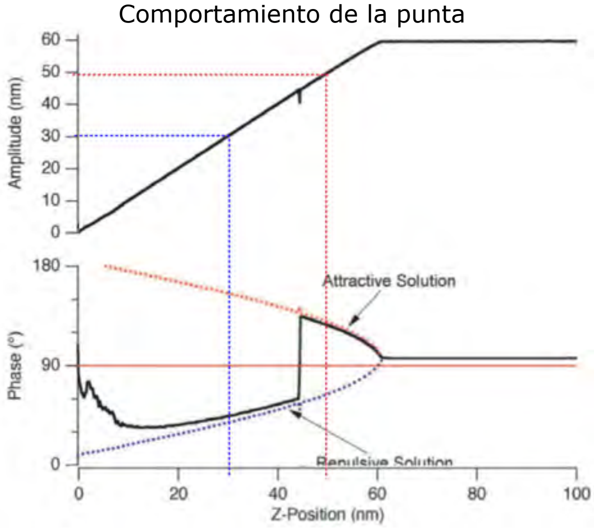


Fuente: AR Applications guide (2018)

Ventajas del modo Tapping:
- Protección de la punta (mantiene afilada)
- Ausencia de fuerzas aplicadas sobre la muestra
- No hay fuerza lateral
- Alta resolución lateral 1-5 µm

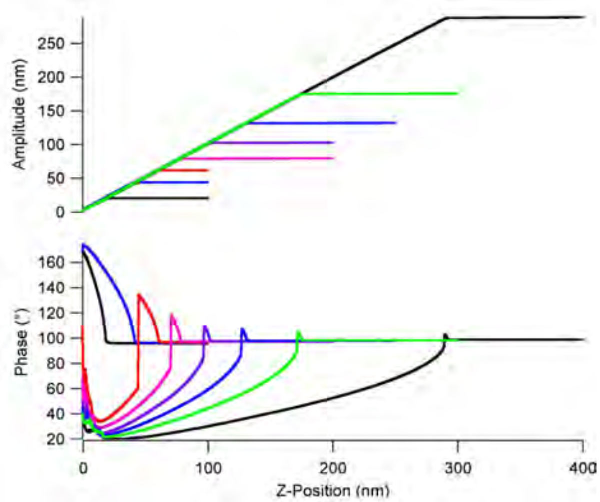
MODO REPULSIVO Y ATRACTIVO

Comportamiento de la punta



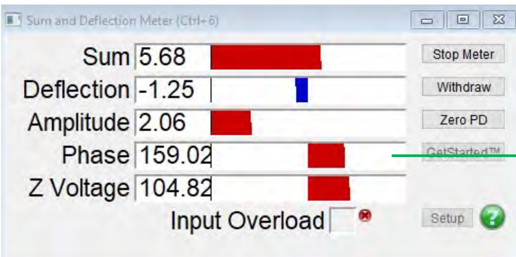
Fuente: AR Applications guide (2018)

Efecto de las propiedades de la punta



Fuente: AR Applications guide (2018)

¿ATRACTIVO O REPULSIVO?



Atractivo >90°
Repulsivo <90°

Modo repulsivo
Muestras duras
Mejor resolución

Modo atractivo
Muestras blandas
Se cuida la punta

Para conseguir el modo A o R se necesita:

Modo repulsivo	Modo atractivo
"free amplitude" altas	"free amplitude" baja
Puntas rígidas (~40 N/m)	Puntas flexibles (~1-10 N/m)
Drive frecuency más baja que la resonancia	Drive frecuency más alta que la resonancia
Bajo Q	Alto Q
Punta aguda	Punta redondeada

MODOS DE OPERACIÓN

Morfología
- Tapping mode (AC mode)
- Contact mode

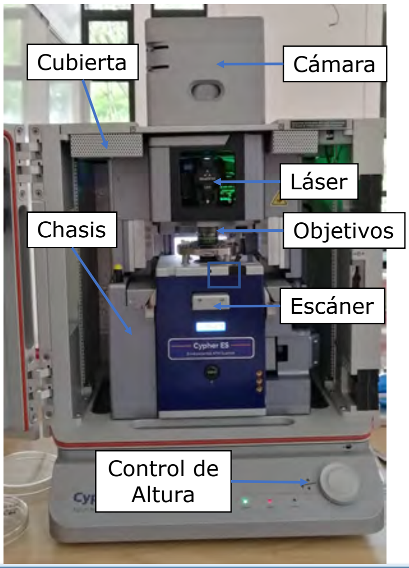
Propiedades mecánicas
- Force Curves / Force Volume
- Fast Force Mapping (FFM)
- Lateral Force Mode (LFM)

Propiedades eléctricas
- Electrostatic Force Microscopy (EFM)
- Kelvin Probe Force Microscopy (KPFM)

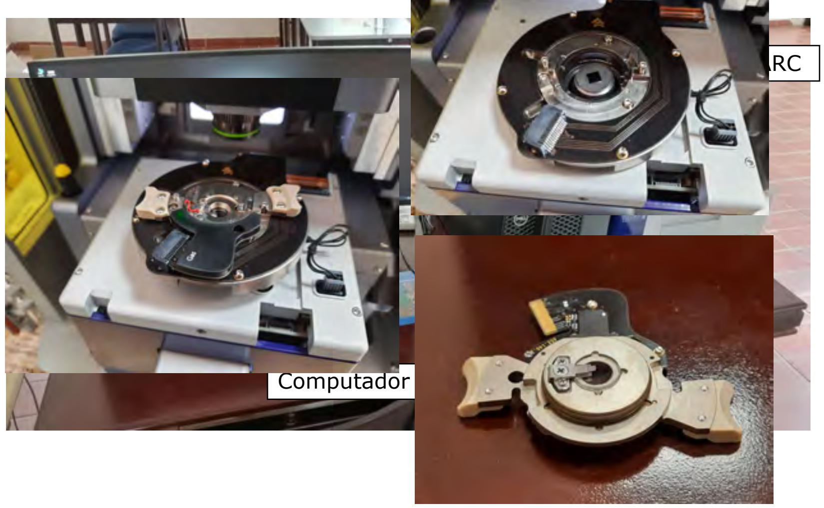
Para destacar- Chypher ES
- Modo medición en líquidos
- Control de temperatura (0-120°C)
- Celda electroquímica

Otras propiedades o modos
- Piezoresponse Force Microscopy (PFM)
- Magnetic Force Microscopy (MFM)
- Nanolithography
- Nanomanipulation
- Piezoresponse Force Microscopy (PFM)
- Switching spectroscopy PFM

PARTES DEL EQUIPO



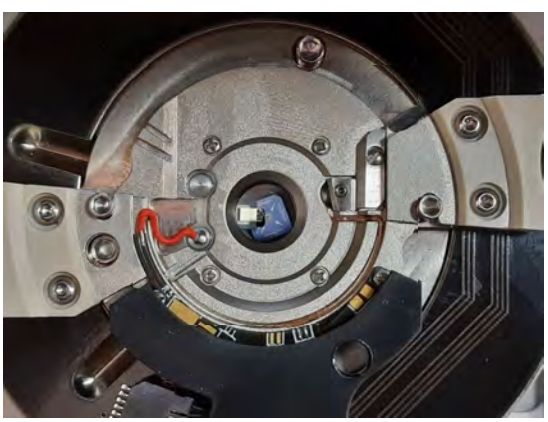
Introducir la muestra



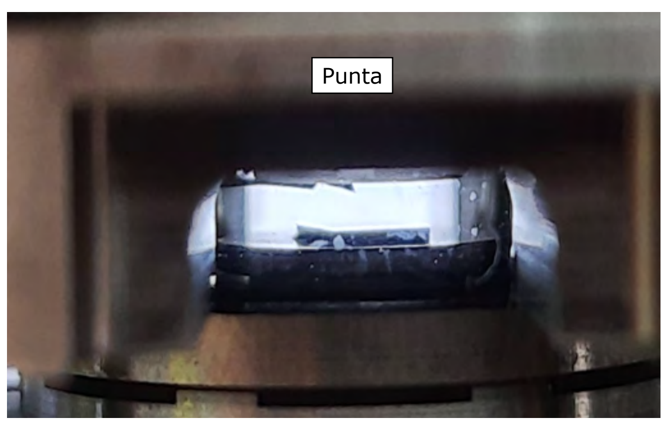
Módulo 1- Capacitación AFM

9

POSICIONAMIENTO DE LA MUESTRA



Vista superior



Vista lateral

Módulo 1- Capacitación AFM

10

CUIDADOS DEL EQUIPO

Ambientales

- Temperatura de la habitación: 10-35°C
- Humedad relativa: ≤50%
- Ruido acústico: <50 dB

Hardware

- El equipo debe mantener encendido
- Conexión a una UPS de 500W
- Evitar aspersión de solventes o desinfectantes.
- Evitar poner elementos sobre ARC y el AFM
- Manipulación de puntas

Riesgos del usuario

Fuente: Chypher user guide (2018)

ómicas

Aliados

CIAT International Center for Tropical Agriculture · cenicaña · FEDEARROZ Federación Nacional de Arroceros · NIAB · intelecto Soluciones y Tecnología · HITECH Automatización S.A.

Caltech · Ghent University · 東京大学 The University of Tokyo · ILLINOIS

Pontificia Universidad Javeriana Cali · IES Ancla · Universidad del Quindío · Universidad de Ibagué · Universidad de los Llanos · Universidad de los Andes Colombia · Universidad ICESI · Pontificia Universidad Javeriana Bogotá

Apoyan

El futuro es de todos Gobierno de Colombia · COLOMBIA CIENTÍFICA