In touch with Atoms.
A gallery of atomic resolution.

Cu (111) Metal
Si (100) Semiconductor
SrRuO2 Exotic oxide
Graphite HOPG Bi-dimensional crystal
Co-TPP on Cu(111) Functional molecules
H2O on Au (111) Snowflake :)

THE UNIVERSITY OF BRITISH COLUMBIA
Democritus
460-370 BC

Atomic hypothesis

The theory of Democritus held that everything is composed of "atoms", which are physically indivisible; that between atoms lies empty space; that atoms are indestructible; have always been, and always will be, in motion; that there are an infinite number of atoms, and kinds of atoms, which differ in shape, and size.

Democritus meditating on the seat of the soul by Léon-Alexandre Delhomme. 1868.
The case for the existence of atoms...

- The indivisible chemical elements: (1777) Antoine Lavoisier
- The Periodic Table: (1871) Mendeleyev
- Statistical Mechanics: (1890) Boltzmann
- X-Rays: (1895) Röntgen
- Nucleus and electrons: (1910) Rutherford
- Quantum Theory: (1913) Bohr
What is an atom?

The “Rutherford” atom.

A lithium atom.
Or three electrons “orbiting” around a nucleus made of three protons and four neutrons.
The source of order in the Mendeleyev table originate in the intimate electronic shell of atoms.
Tight binding description:
New electronic structure is build upon the elemental wave function of each atoms

\[ \Psi(r) = \sum_{n,R} b_{n,R} \psi_n(r - R) \]

Electronic Molecular Orbitals
Electronic wavefunction is build upon the periodicity of the crystal lattice

$$\psi_{nk}(r) = e^{ik \cdot r} u_{nk}(r).$$

Bloch wave equipotential in AsGa lattice

Band structure of GaAs
Note the semiconducting Gap at Ef=0
Can we “see” atoms?

What is seeing?
Projection of an interacting particle from an object onto a detector

Not with usual photons.
Limited by diffraction at 500nm
In touch with atoms

- **X-ray diffraction:** Atoms in the reciprocal space (1920) P. Debye.
- **Field Ion Microscope:** Atoms on a tip (1971) E.W. Muller and K. Bahadur.
- **Transmission Electron Microscope:** 3D sample with atomic resolution (1931-1970) Ruska to A. Crewe.
- **Scanning Probe Microscope:** The almighty microscope for surface (1981) G. Binning and H. Rohrer
Seeing atoms: X-Rays diffraction

The Fresnel two-slit experiment

Coherent diffraction of an organized arrays of atoms.

Typical X ray diffraction cliche

Atoms favor periodic arrangement
Electron Microscope

The original (1930)

Principle of operation

The modern (2010)
Electron Microscope

Inverse Fourier Transform of a diffracted electron beam on a crystalline multilayer

High Resolution Scanning Electron Microscope
Electron Energy Loss Spectrometer
Field Ion Microscope

The Original FIM

Modern Zeiss FIM

Principle of operation
Field Ion Microscope

Scanning Electron Micrograph of a W tip

Atomistic modelling of the tip apex

Field Ion Micrograph

Sharpening a tip one atom at the time!

20nm
The Scanning Tunneling Microscope

Bring a tip at within atomic reach to a surface
Measure a tunneling current (It) with a high gain amplifier
Stabilize the tip with a feedback loop on It
Track the tip height variation as the tip is raster in the XY plane
Process the signal to form a 3D rendering of the tip trajectory

Electron tunneling 101

Plane wave travelling through an energy barrier defined by the work function of the sample from the sample to the tip separated by an external bias eV.

$I_e$ decays exponentially with an increasing barrier width. Characteristic decay length equal $10^{-10}m$, the size of an atom!

$I_e \approx U e^{-2\frac{\sqrt{2m\Phi}}{\hbar}D}$

$40*40nm$ STM image of the Silver 111 surface showing four distinct atomic terraces.
Density Functional Theory vs. STM on SrRuO

Charge density isolines from DFT at a height of 2.13 Å.

High Resolution STM showing Sr centered resolution
Atomic manipulation

Pushing Carbon Monoxide around
The atomic domino computer I

One CO molecule is stable
Two CO molecules are stable
But three CO molecules want to form a perfect triangle

Molecule Cascades
The atomic domino computer II

Information transport

Building an AND gate
The atomic domino computer III

A 200nm^2 three input sorter. Its CMOS equivalent is 10^5 bigger!
Other fields we are working on.

High Tc-superconductivity

Quantum Spintronics

Architecture in the NanoCosmos

Efficient organics light harvesting device
Building a state of the art STM.

Instrumentation: from a few pennies to M$++

From a single piezoelectric tube to highly controlled environment
Sample: building one atom at the time

Molecular beam epitaxy in Ultra High Vacuum
A quest for lower temperature

Freeze it!

- Room Temperature 300K
- Isolation Neck: Vacuum + Radiation shield + low conduction mechanical support
- Helium 4 Bath 4.2 K
- He4/He3 Joule Thompson stage. 1K
- He4/He3 Dilution stage 50mK
- STM Head in a 7T magnetic field

Freeze it!
A vibration free space

Laboratory for Advanced Imaging Research
State-of-the-art laboratory and scanning probe microscopes for the study of novel quantum materials at the atomic scale.
STM head

From millimetres down to angstrom

- Body
- 3D Inchworm 10*5*5mm travel
- 3 S-SMA 40 GHz connectors
- In situ Tip exchange
Conclusion

Democritus was right!
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