

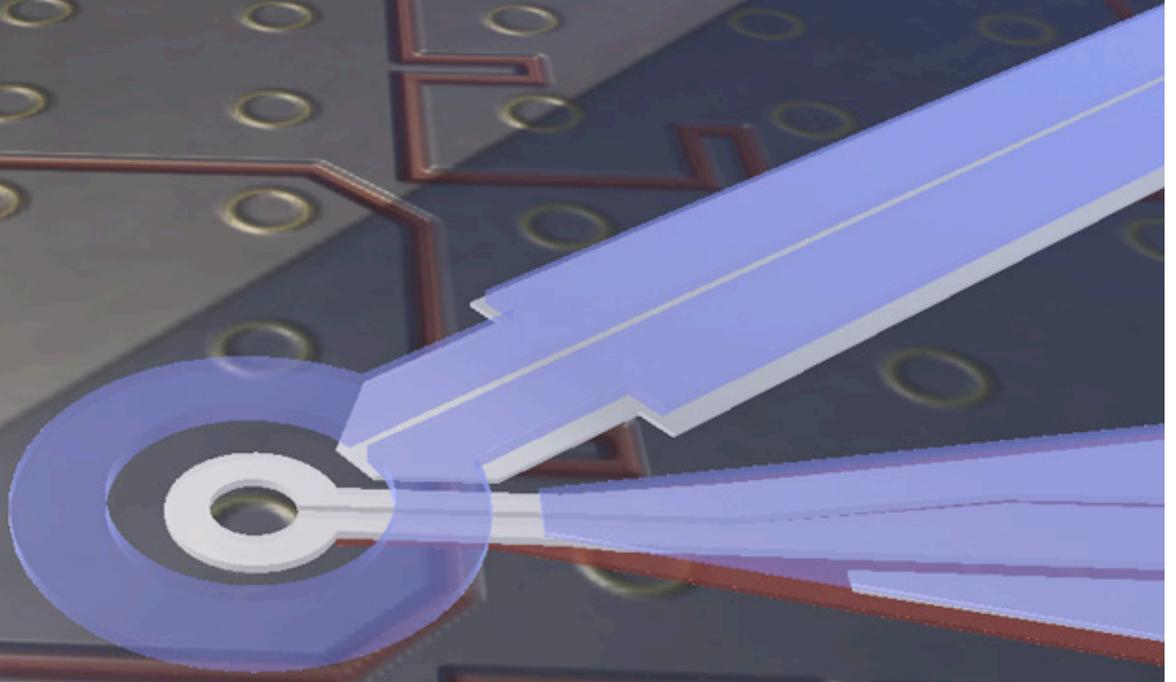
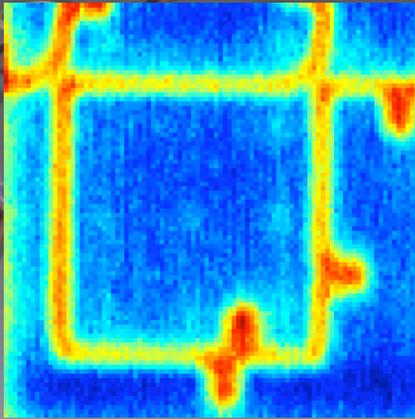
Trends in Measurements at the Nanoscale

Kam Moler, Director, the Center for Probing the Nanoscale

NSF NSE Meeting, December 7 2009

The Moler Lab

Spin contamination on metal wires



CENTER FOR PROBING THE NANOSCALE

An NSF Nanoscale Science and Engineering Center

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“One must be able to measure and quantify phenomena in order to understand and use them, which is true also for nanoscale phenomena.”

--Small Wonders, Endless Frontiers: Review of the National Nanotechnology Initiative, report from the National Research Council, June 2002

engineers regarding the theory and practice of these probes.

- To *transfer our technology to industry* so that corporations can manufacture and market our novel probes worldwide.
- To *inspire thousands of middle school students* by training their teachers at a Summer Institute for Middle School Teachers.

CPN Outreach Partnership with The National Hispanic University

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CPN and Agilent Co-sponsor Seed Grants for Innovative Research

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Enhanced Resolution SQUID Microscopes

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CENTER FOR PROBING THE NANOSCALE

An NSF Nanoscale Science and Engineering Center



Two decades of nanoscale imaging enabled by inventions with
high spatial resolution + modern information processing

Current Trends in Measurements at the Nanoscale

3-dimensional imaging

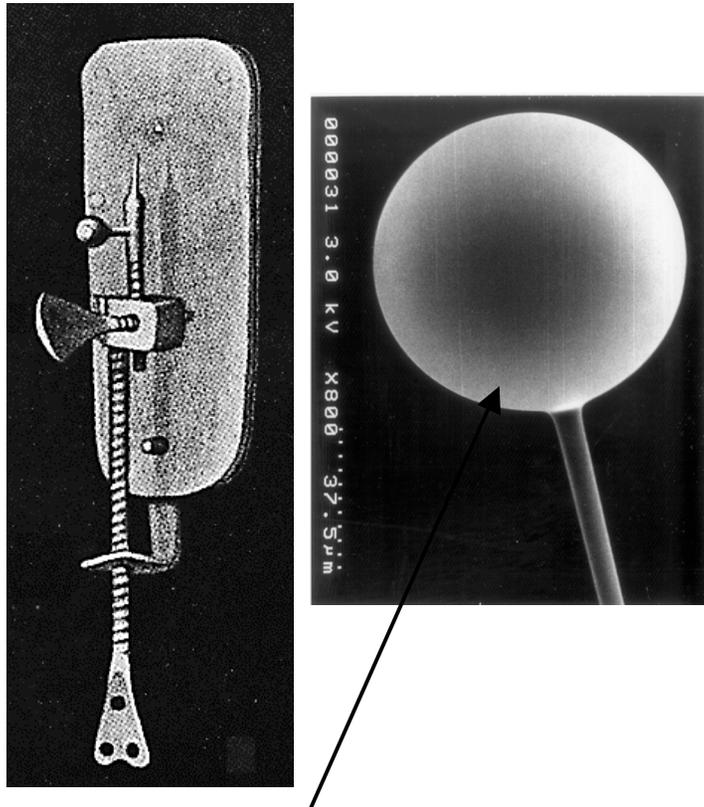
“3+1”-dimensional imaging: dramatically increased
time resolution

N-dimensional imaging: Measurement of multiple
physical, biological, & chemical properties, as a
function of multiple parameters $x, y, z, t, T, H, E, P, \dots$



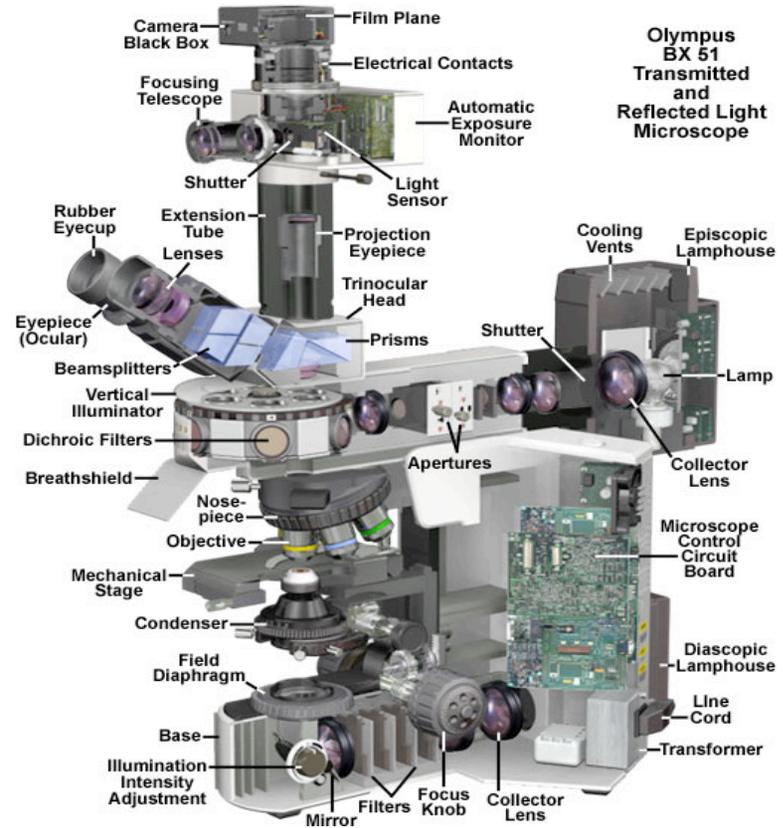
Optical microscopes

Van Leeuwenhoek's microscope (1673)



- Little glass sphere acted as a lens
- Discovered bacteria, blood cells, etc.

Modern microscope

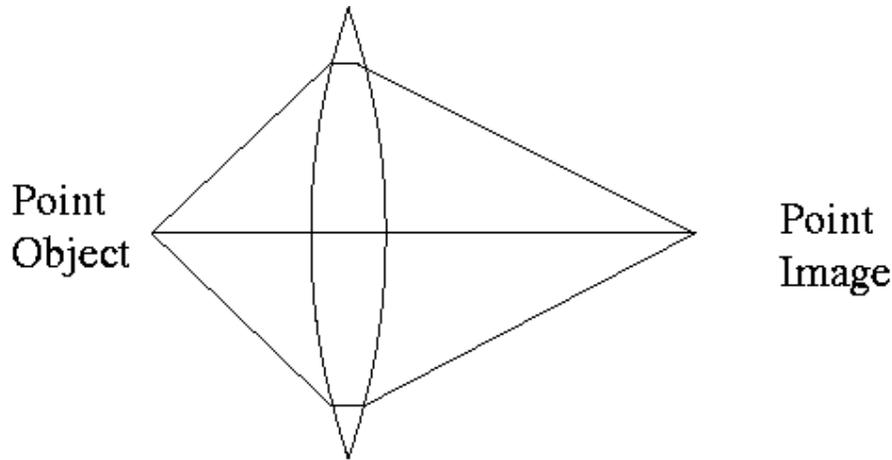


One of the most important tools to characterize materials (dead or alive!)

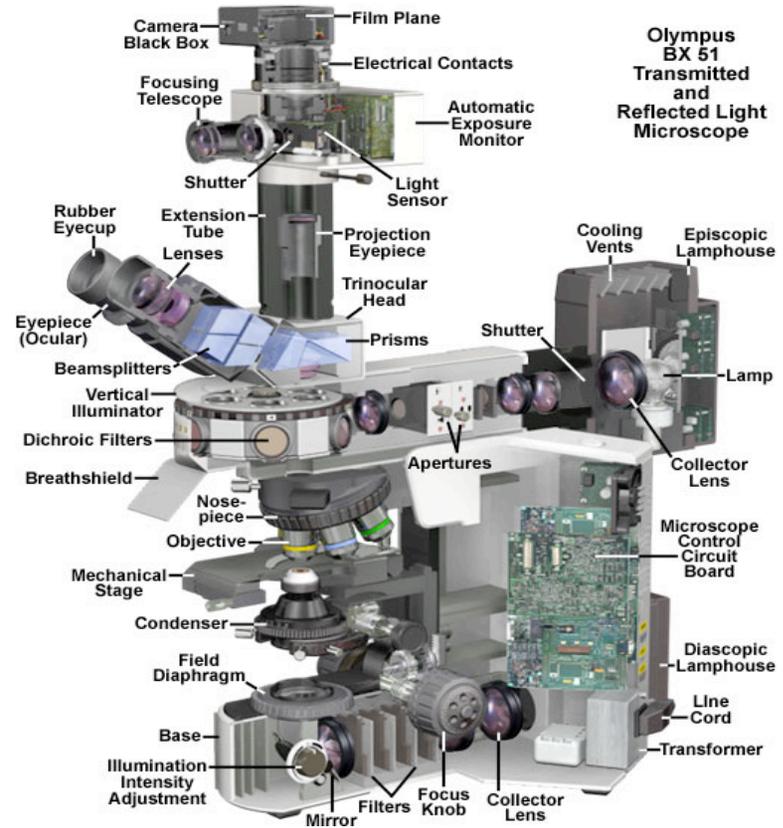
From: Mark Brongersma

Optical microscopes

Ray optics with lenses =>
great resolution even at a distance!



Modern microscope



One of the most important tools to characterize materials (dead or alive!)

Lens Image:

<http://www.physics.smu.edu/~scalise/emmanual/lens/lab.html>

The diffraction limit for optical measurements

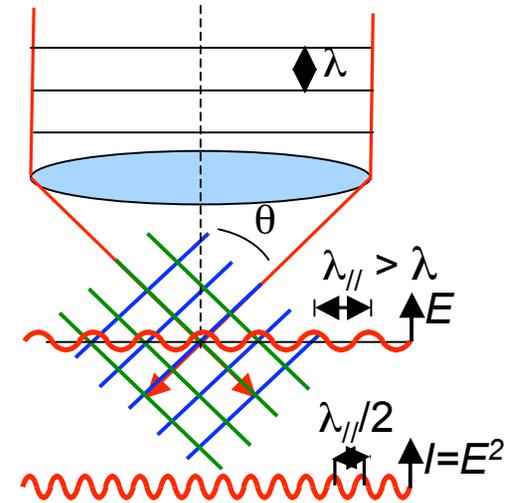
$$\Delta r \geq \frac{1.22\lambda}{2n \sin \theta}$$

Δr = minimum resolvable distance between two objects

λ = wavelength of light

n = refractive index of the lens medium

θ = semi-angle of the objective used for focusing (or collecting)



high quality lenses $\Delta r \approx \lambda/2 \approx 250 \text{ nm}$ for visible light

From: Mark Brongersma

We'd like to measure many properties:

Topography
Structure
Composition
Optical properties
Mechanical properties
Chemical properties
Temperature
Electric charge / field / voltage
Magnetic field / spins
Quantum state
...

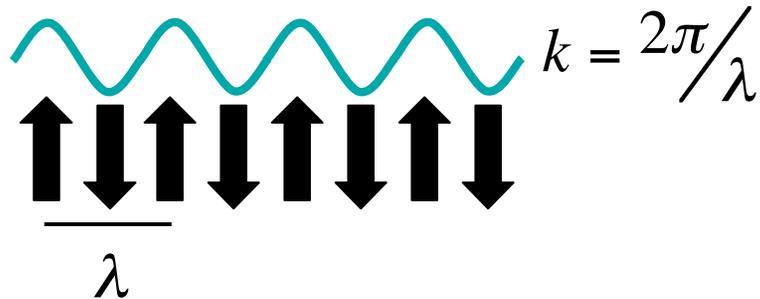
For many of these properties, we've always needed local sensors, even at the humanscale.

And, many physically interesting properties do not have a helpful "far-field" comparable to light (or beams of other particles)

Other quantities have no macroscopic regime example: magnetic fields

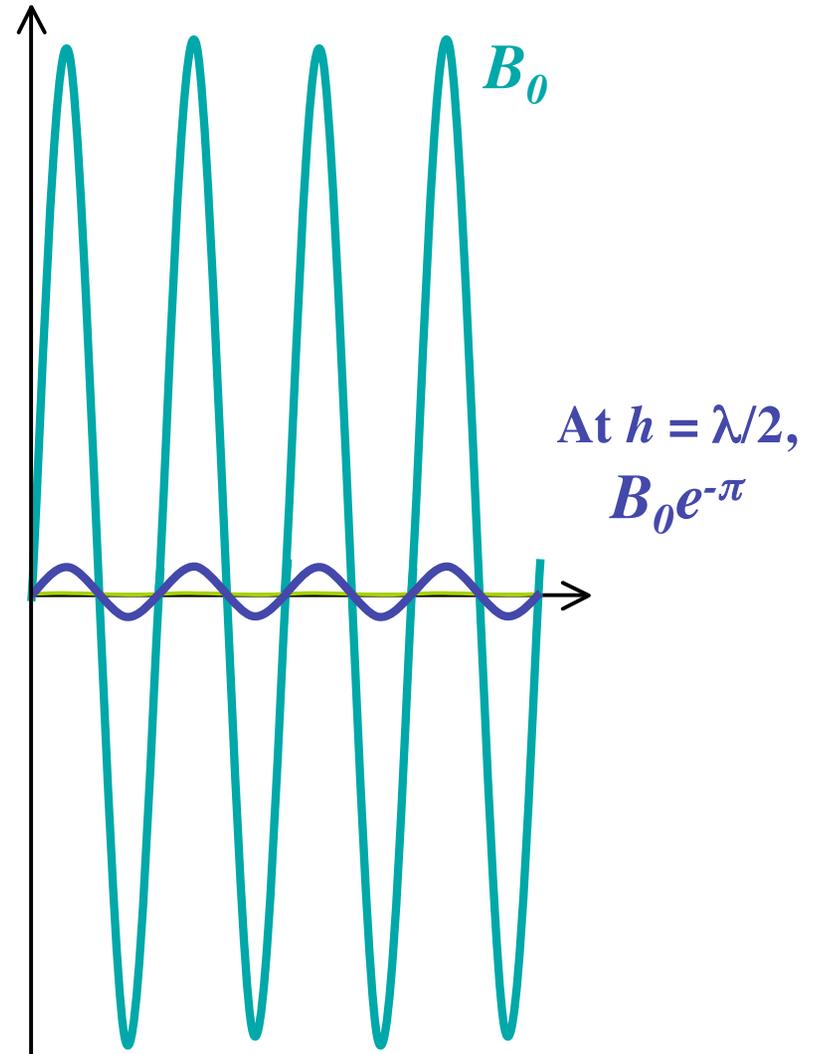
Hypothetical magnetic field at a surface

$$B_z(x, z = 0) = B_0 \cos(kx)$$



Resulting magnetic field at a distance h

$$B_z(x, z = h) = B_0 \exp(-kh) \cos(kx)$$



Achieving nanoscale imaging

- Beams with wavelengths smaller than optical light
 - X-rays, electrons, ions,
- Near-field or local probes
Requires scanning + numerical or experimental deconvolution and modeling to achieve 3D imaging
- Point-like sources inside the sample
 - Physical point sources.
Example: fluorescent molecules
 - Resonantly induced local sensitivity.
Example: magnetic resonance

Near-field Optical Microscope

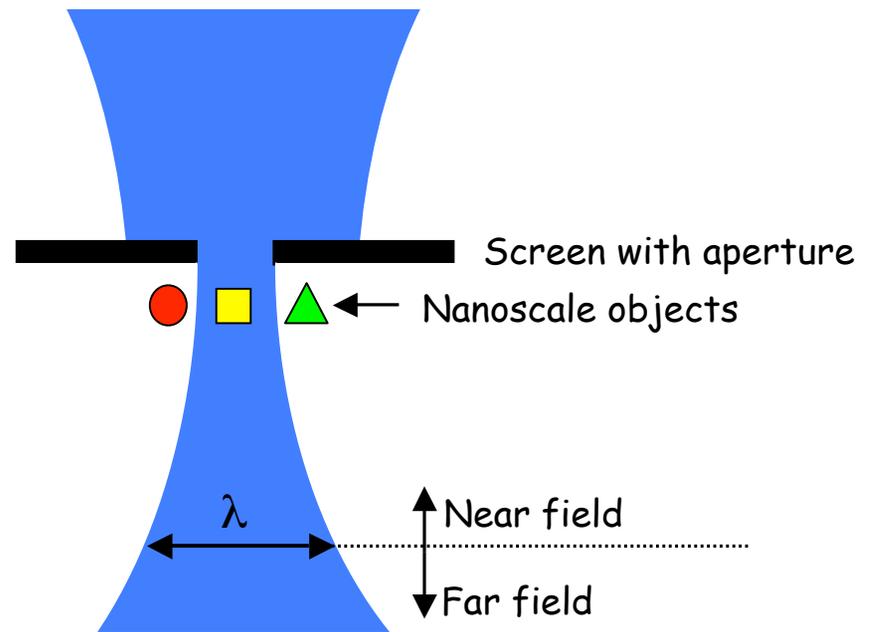


Image: Mark Brongersma

General considerations for nanosensors

spatial resolution

bandwidth

invasiveness

usability:

fast turnaround

accessibility

range of operable environments

quality of information:

interpretability

precision/sensitivity

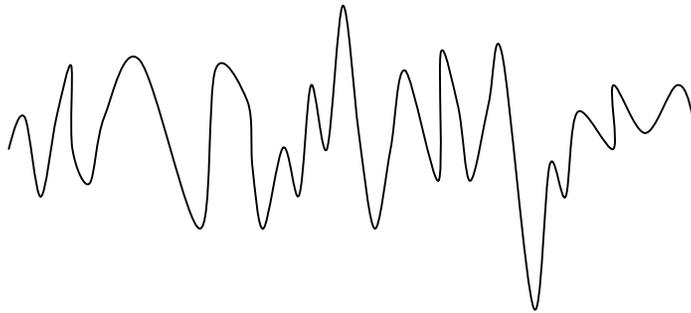
Signal-to-Noise at the Nanoscale

Less stuff
=> less signal

Fewer particles
=> more fluctuations
=> more noise

Quick Introduction to Noise Spectra

Time Trace $y(t)$



Fourier Transform

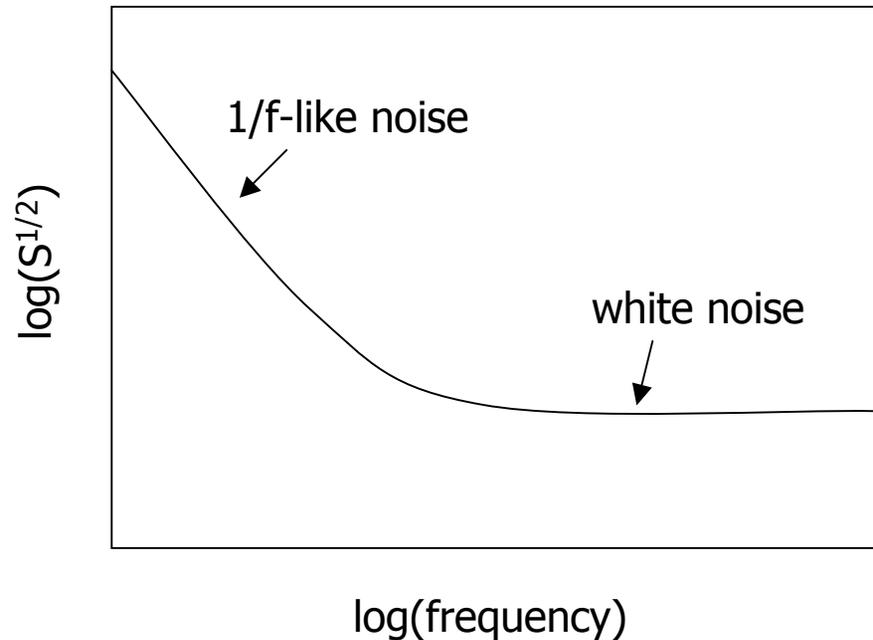
$$Y(f)$$

Power Spectral Density or PSD

$$S(f) \equiv Y^* Y$$

“Noise” or “Sensitivity”
 $S^{1/2}$

Measured in, for example, Volts/Hz^{1/2}



Why not just measure longer?

Reason #1: takes too long

Sensitivity $S^{1/2}$ is measured in Units/Hz^{1/2}

$$\text{Minimum detectable signal} = \frac{S^{1/2}}{\text{Square root of the measurement time}}$$

(with S/N = 1)

Reason #2: we want time resolution!

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high spatial resolution + modern information processing

Current Trends in Measurements at the Nanoscale

3-dimensional imaging

“3+1”-dimensional imaging: dramatically increased
time resolution

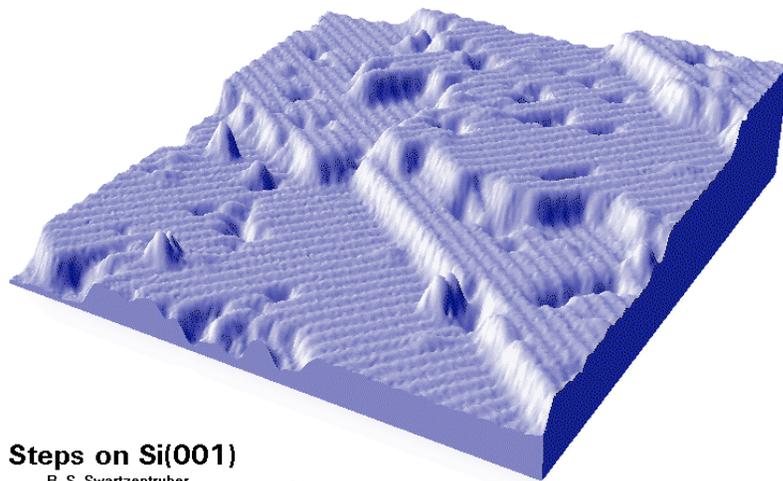
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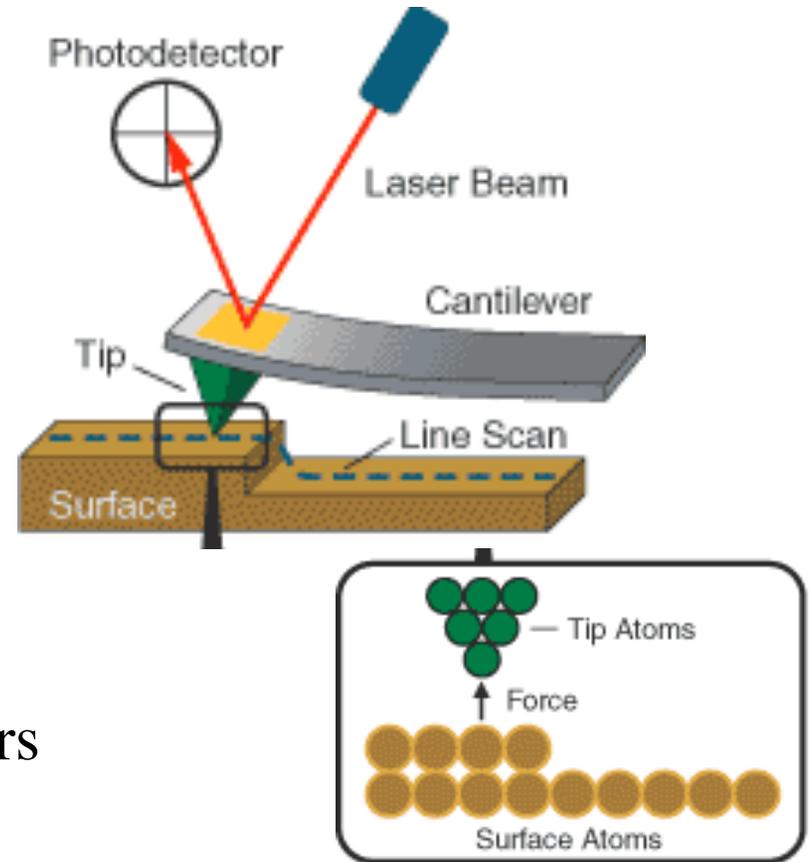
Increasingly good commercial tools are increasingly accessible



Increased usability, accessibility, and flexibility of (some) Scanning Probe Microscopies



Steps on Si(001)
B. S. Swartzentruber



But.... many types of scanned probes remain inaccessible to many researchers

Image credits:

A: http://www.molec.com/what_is_afm.html

B: http://www.sandia.gov/surface_science/stm/3dsteps.gif

Increased abilities and accessibility of commercial “beam” tools

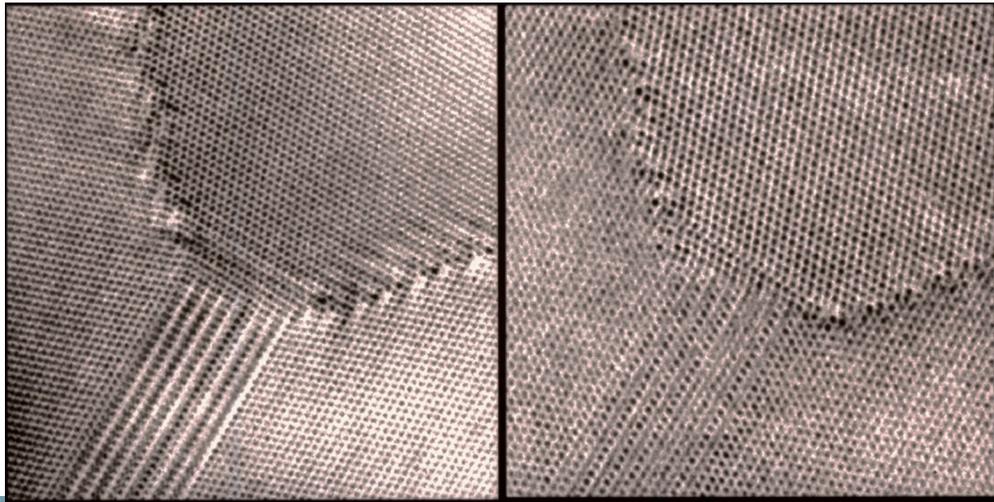
Transmission Electron Microscope

Scanning Electron Microscope

New types:

Scanning Helium Microscope

NanoSIMS



Specific trends in state-of-the-art measurement technologies

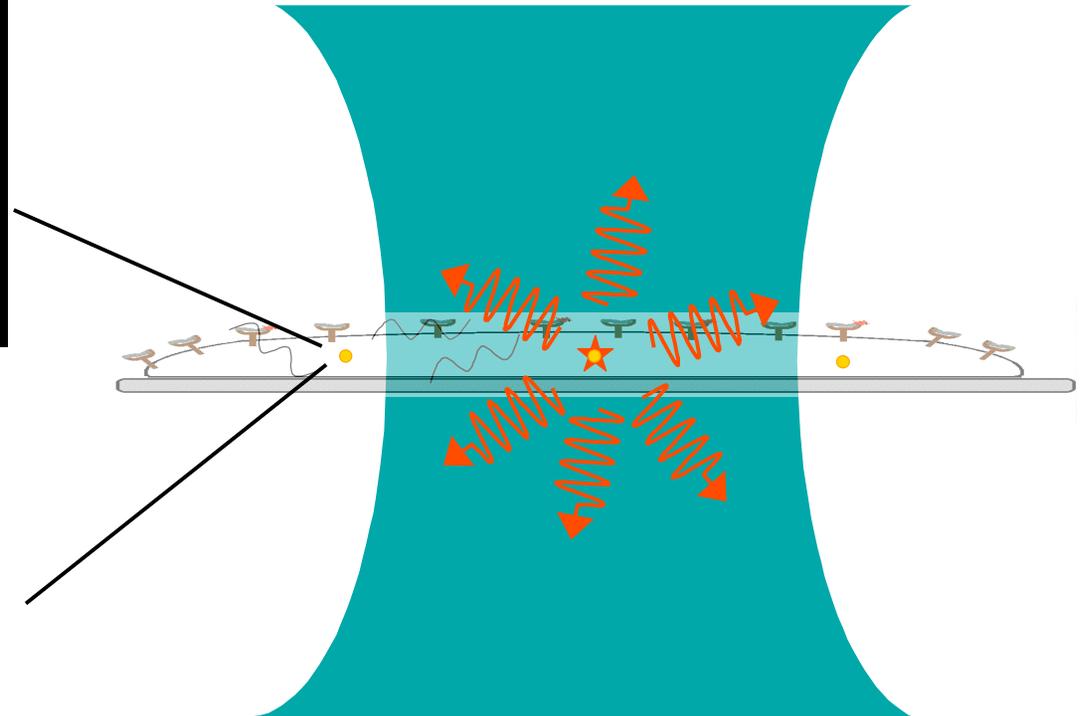
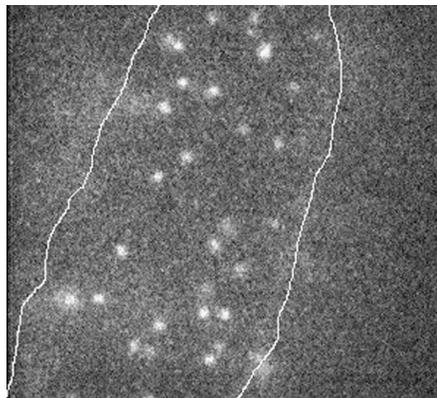
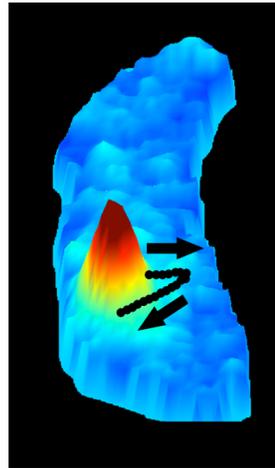
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2. Clever techniques enable sub-wavelength, three-dimensional imaging, even in biological systems.

Visualizing Single Molecules in Living Cells

W. E. Moerner

Bacterial actin inside a living bacterium
Labeled with EYFP
Kim et al. PNAS 2006

+/- 15 nm position
resolution



Single immune system proteins in the CHO cell plasma membrane, Vrijlic et al. BPJ 2002, 2005
Protein binds peptides, peptides have fluorescent label.

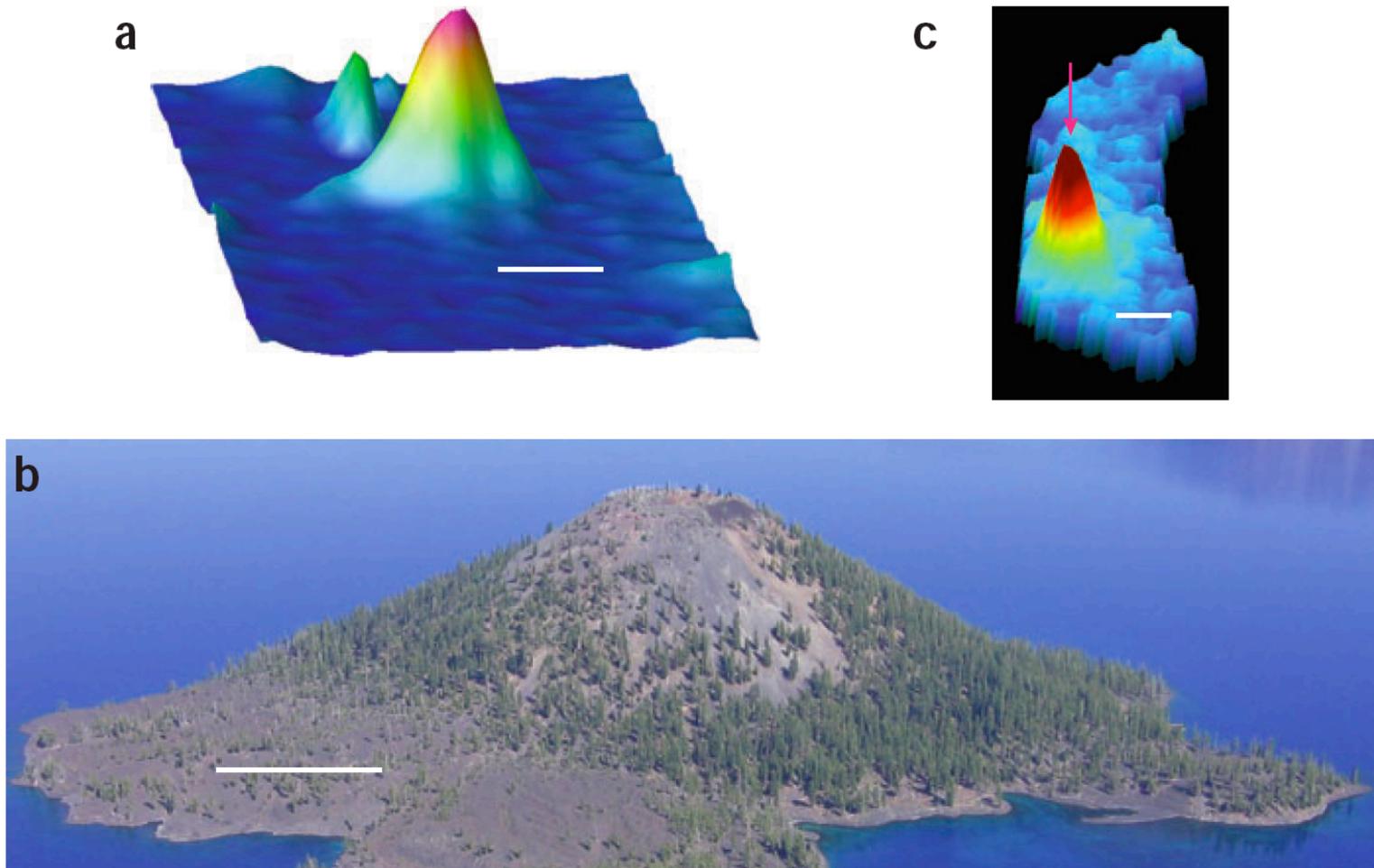


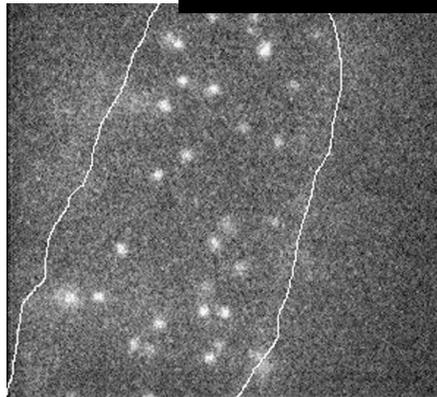
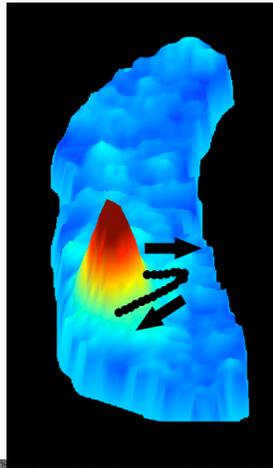
Figure 1 | Measuring mountain peaks for superresolution imaging. (a) Position-frequency image of single molecules of pentacene in a crystal¹, as a pumping laser beam is moved across the sample and the fluorescence is recorded. (b) It is easily possible to walk to the top of the cinder cone in Crater Lake to find the position of the peak accurately. (c) Similarly, in a living bacterial cell (blue)², the image of a single fluorescent protein molecule appears as a wide spot due to fundamental diffraction effects, but one can determine its position (pink arrow) to much less than the width of the “mountain.” By turning single-molecule light sources like this on and off in a cell, researchers have recently obtained superresolution images. Scale bars: **a**, 5×10^3 nm; **b**, $\sim 120 \times 10^9$ nm; **c**, 250 nm.

Visualizing Single Molecules in Living Cells

W. E. Moerner

Bacterial actin inside a living bacterium
Labeled with EYFP
Kim et al. PNAS 2006

+/- 15 nm position
resolution



Diffusion of Class II MHC in CHO cells

12 x 12 microns

Cell_2067

M. Vrljic, S. Nishimura

Moerner/McConnell Groups

Single immune system proteins in the CHO cell plasma membrane, Vrljic et al. BPJ 2002, 2005
Protein binds peptides, peptides have fluorescent label.
Proteins move around on the cell surface in real time!

Overlapping Peak Problem

It's cool that they can “see” single molecules moving in living cells!
But what if we want to see the *whole cell* with nanoscale resolution?
Using digital techniques to identify the sub-wavelength identification of the source only works for isolated sources.

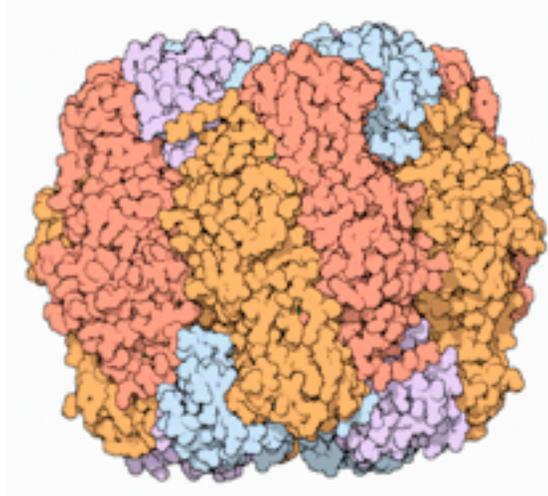
Solutions:

- 1) Photoswitch: turn different single molecules on and off.
- 2) Resonant techniques.

Specific trends in state-of-the-art measurement technologies

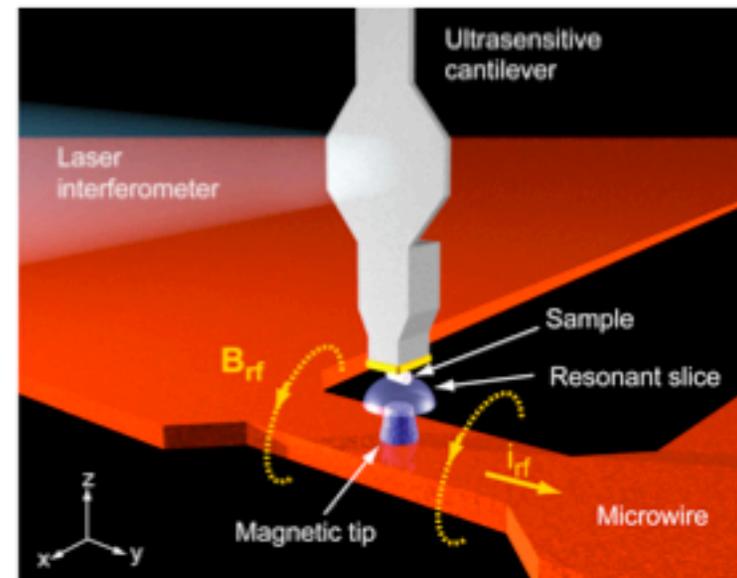
1. Increasingly good commercial tools are increasingly accessible
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3. Magnetic Resonance Force Microscopy: Magnetic Resonance Imaging is truly nano now

The Quest for a Molecular Structure Microscope

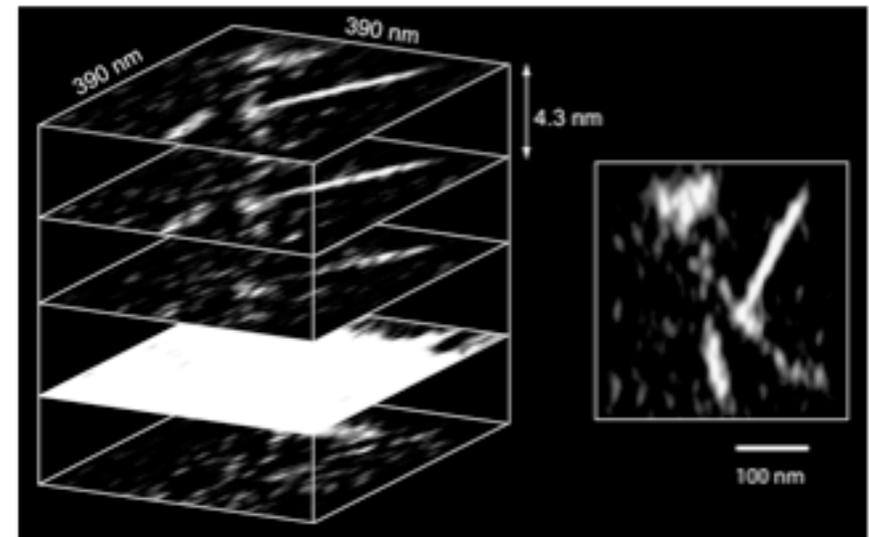


- Can a microscope be built that can directly image the 3D structure of molecules?
- Molecular structure is key to understanding biological structure and function
- Most proteins in your body have no known structure due to limitations of current techniques

Nanoscale MRI using a magnetic resonance force microscope



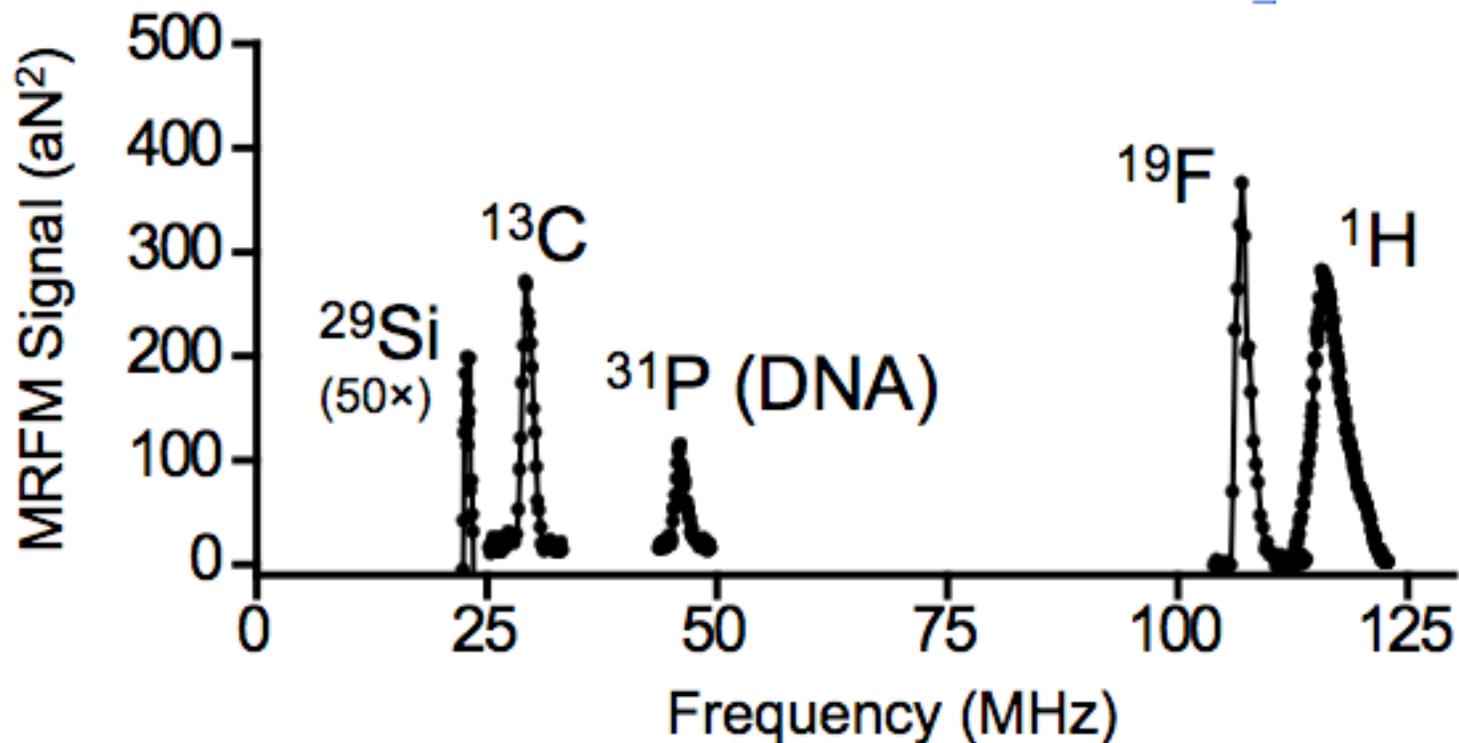
3D map of hydrogen nuclear spin density in virus particles



Elemental Selectivity of NMR-MRFM

<u>Element</u>	<u>Gyromagnetic ratio</u>
^1H	42.6 MHz per Tesla
^{13}C	10.7
^{19}F	40.0
^{31}P	17.2
^{29}Si	8.46

Signal vs. rf excitation frequency for $B_0 = 2.7\text{ T}$

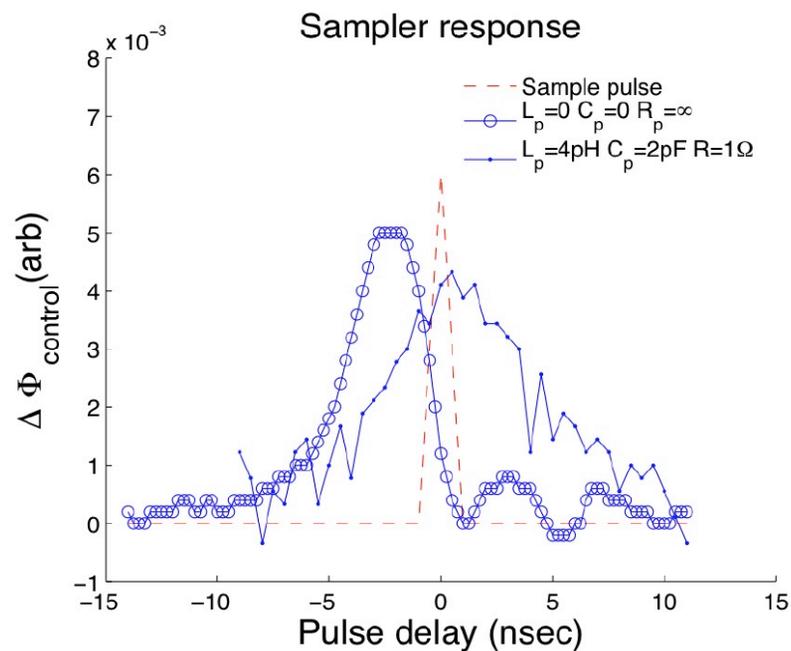
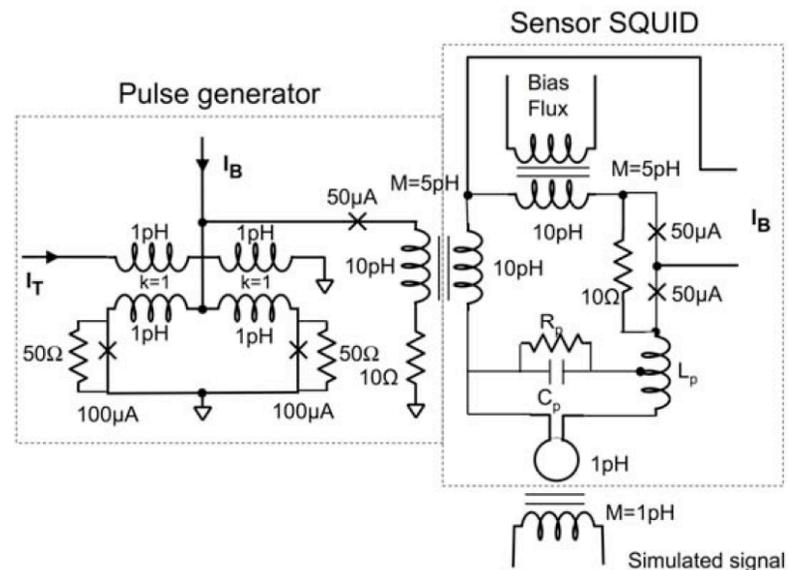
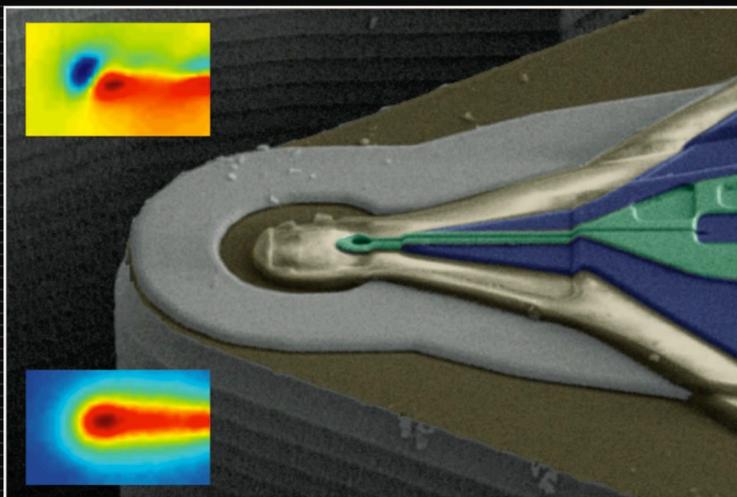


Specific trends in state-of-the-art measurement technologies

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4. Advances in electronics and lasers allow "tabletop" time resolution, especially for periodic phenomena



APPLIED PHYSICS LETTERS

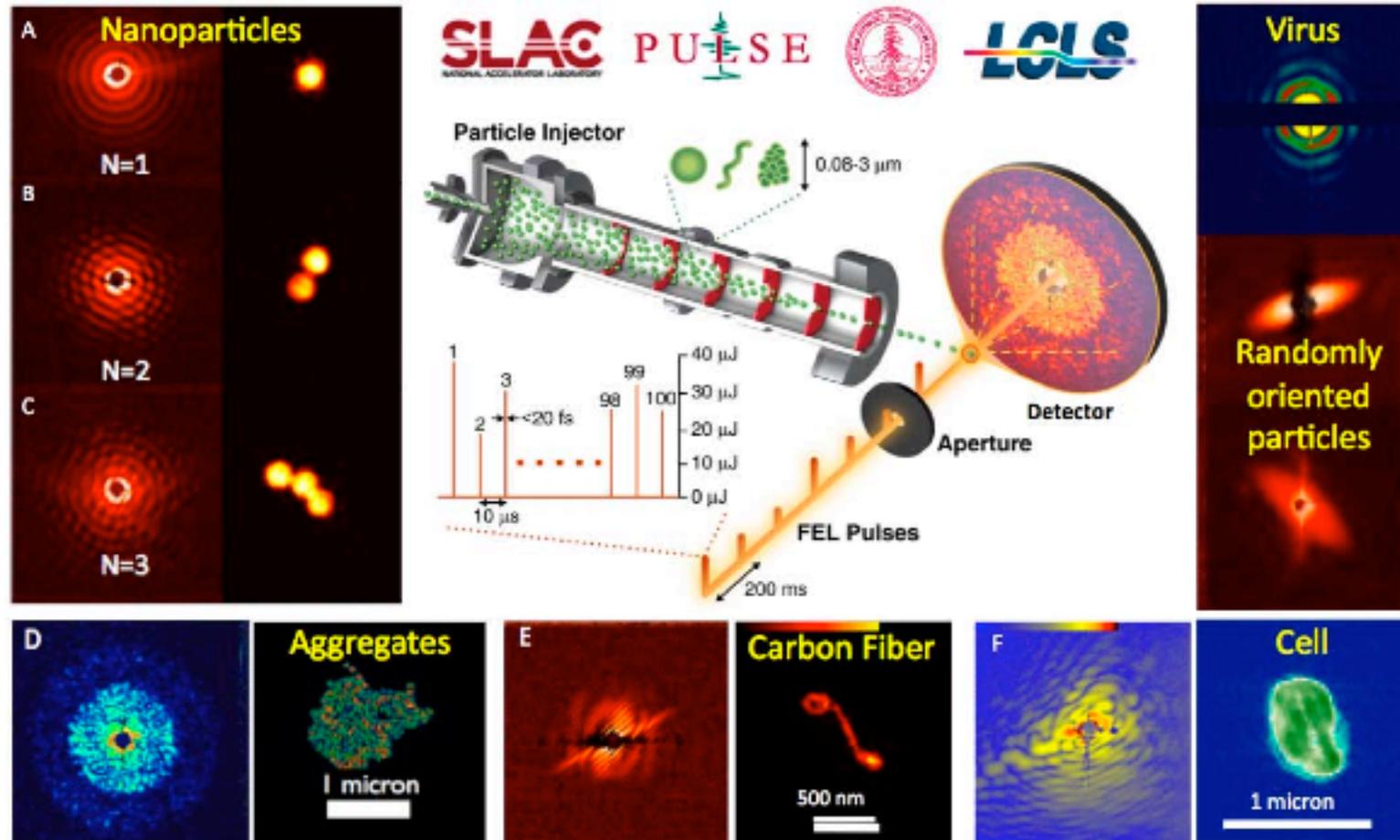


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5. Unique accelerator-based fast, high-resolution imaging capabilities.

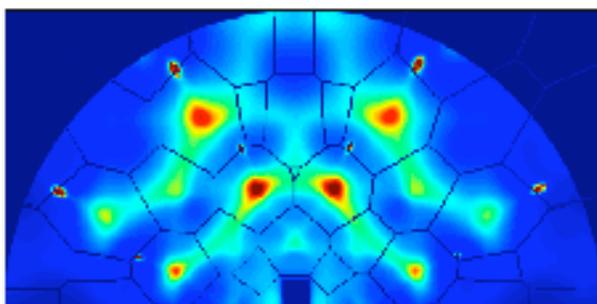


Nonperiodic Imaging

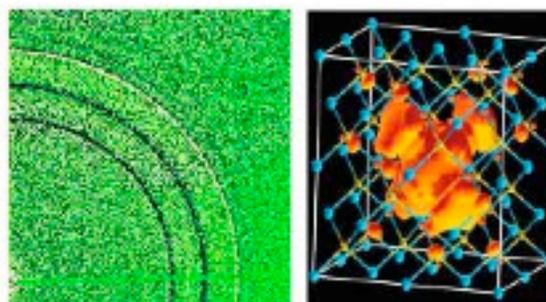


Nonperiodic nanoscale imaging at LCLS involves reconstructing x-ray scattering data from single nanoparticles. The frontier science questions under study range from nanobiology to aerosol chemistry to combustion

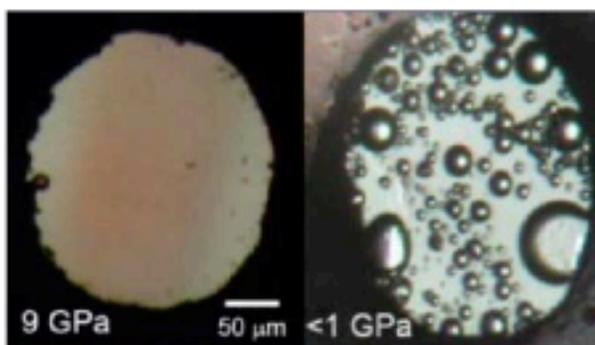
Nonequilibrium Phonon Dynamics



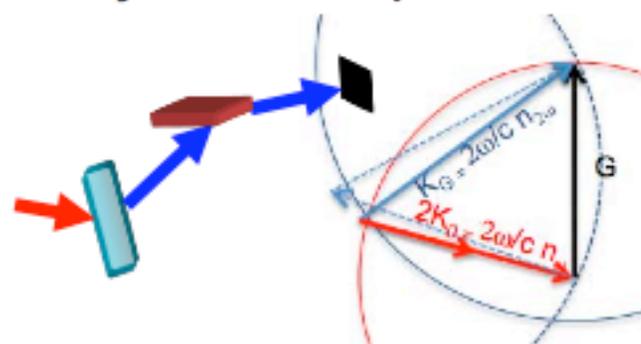
Nanoscale Phase Transitions



X-ray Modification of Materials



X-ray Nonlinear Optics

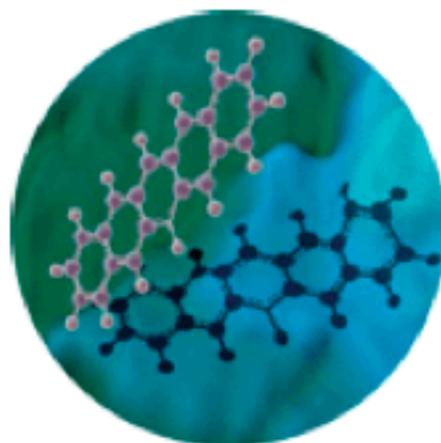


Ultrafast x-rays can track nonequilibrium dynamics in solids with atomic-scale resolution in time and space and with atomic specificity. LCLS is a unique tool for these studies.

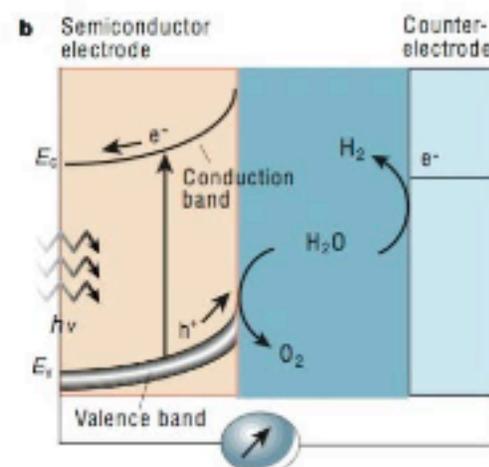
Ultrafast Processes in Light Harvesting Materials



Dynamics of electron relaxation in nanostructured materials



Dynamics of exciton and charge transport in organic semiconductors



Dynamics of water splitting in photoelectrochemical cells

Characterizing and Controlling the Transduction of Light to Chemical and Electrical Energy

Ultrafast x-ray and optical techniques can probe the dynamics of charge separation, charge transport, and charge transfer in a variety of light harvesting materials, including organic semiconductors, colloidal nanomaterials, and complex alloys.

Specific trends in state-of-the-art measurement technologies

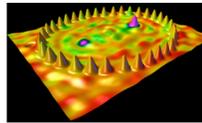
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4. Advances in electronics and lasers allow “tabletop” time resolution, especially for periodic phenomena
5. Accelerator-based unique fast imaging capabilities.
6. Nano-imaging continues to capture public imagination.

Physics News In 1999

A Supplement to APS News

Edited by Phillip E. Schewe and Ben P. Stein
Public Information Division, American Institute of Physics

Physics News in 1999 is the most recent in a series of annual surveys of important physics news prepared by AIP. All of the entries in this compilation are fully cited and available in the Physics News Update. Many of these items are featured in the "Physics Update" page in Physics Today magazine, where they are prepared by Richard M. Jones and Aubrey T. Leahy.



Science Policy in 1999: The Year in Review

AUGUST

The New York Times

A18 YNS

THE NEW YORK TIMES NATIONAL THURSDAY, FEBRUARY 3, 2000

Peeking at an Atom in a Hall of Mirrors

By GEORGE JOHNSON

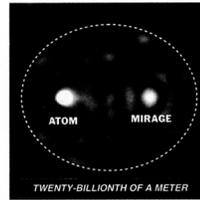
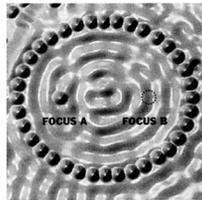
Crossing a barrier that once seemed impassable, physicists in recent years have used a delicate instrument called a scanning tunneling microscope to reach down into the very substrate of matter, feeling the bumps and grooves of atoms and even picking them up and moving them around like so many grains of sand.

In a well-publicized tour de force, I.B.M. researchers in 1990 carefully arranged 35 atoms of the element xenon to spell out their company's initials.

Now, in another demonstration of subatomic nimbleness, scientists have created a kind of quantum reflector, in which an atom placed in one location appears as a ghostly

The 'Quantum Corral'

By placing an atom at one of two focal points in an ellipse of cobalt atoms (which acts like a mirror), a mirage of the inner atom appears at the other focal point with some properties of the original.



ATOM MIRAGE
TWENTY-BILLIONTH OF A METER

TOPOGRAPHIC IMAGE

Shows the arrangement of cobalt atoms on a field of copper.

MAGNETIC IMAGE

Shows the effect of the cobalt atom on the copper background.

news feature

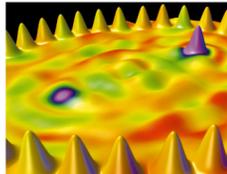
Nanotech thinks big

The science of the incredibly small is shedding its soft-focus image. An anticipated influx of US government funds is nurturing a new wave of interdisciplinary nanoscience research, says Colin MacLachlan.

There is no such thing as a free lunch, it is sometimes said. But ever since Eric Drexler brought the term "nanotechnology" into vogue in his 1986 book *Engines of Creation*, some researchers have felt that the field has been hindered by unrealistic hopes. The term "nanotechnology" is a self-replicating, nanoscale "assembly" that would be used to build larger-scale machines to overcome the dominant "top-down" approach to manufacturing.

The federal nanotechnology is nurturing the respect researchers in the field believe it deserves. This year for the first time, the US government has identified nanoscience and technology as a top research priority. The European Union and other nations are contemplating similar actions, and bright young scientists and engineers are starting to gravitate toward the field. The traditional divide is even more important than the funds at the moment," says Richard Smalley, director of nanotechnology programs at the US National Science Foundation (NSF), and one of the major forces pushing the field to the federal research agenda.

Back to basics
The US Congress has been asked to fund a new National Nanotechnology Initiative, which would double federal funding for the discipline to \$300 million in 2001. When President Bill Clinton launched the initiative



Atomic insights: the scanning tunneling microscope gives nanoscopic views, such as this quantum corrall. The corrall is a ring of cobalt atoms arranged in an elliptical shape on a field of copper. The central peak is a single cobalt atom. The corrall is 20 billionths of a meter across.

nanotechnology programs at the US National Science Foundation (NSF), and one of the major forces pushing the field to the federal research agenda.

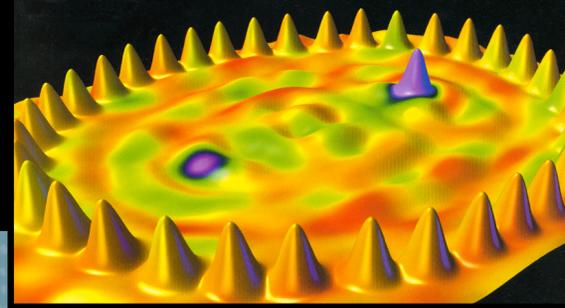
3 February 2000 International weekly journal of science

nature

910.00 www.nature.com

Phantom atoms

- Clinical genomics** Classifying cancers
- Ball lightning** An earthy origin?
- The fossil record** As good as it's long



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IBM Journal of Research and Development

Volume 44, Number 3, May 2000

Directions in Information Technology

news and views

Electrons in the looking glass

Eric Heiler

The scanning tunneling microscope (STM) is a marvel to scientists and the public alike. It has allowed us to see individual atoms as directly "seen" as we have ever before. The technology has allowed us to see an acoustic analog of a sound wave. The speaker, which you place at some point in a room, the speaker plays a note of a given frequency, while you measure power radiated into the room. You would notice a variation in power output by changing either the frequency of the sound or the position of the speaker. The reason is simple: sound reflects off walls and furniture comes back and combines at the speaker to make a reinforcing wave with a given amplitude and phase. This wave makes the speaker do more or less work as it oscillates in and out, depending on the relative phase of the speaker and the returning sound. If you keep the frequency fixed, you could make a plot of power output against speaker position; it would have a double-peak appearance.

If you have followed this acoustic example so far, you are almost there. Now, replace

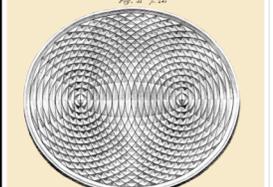


Figure 1: Waves in an elliptical disk of atoms. This diagram by the Miller brothers in 1825 can be seen at the most remarkable hand-drawn scientific illustration ever. It shows what happens when you put droplets of liquid mercury into one focus of an elliptical disk filled with mercury. The experiment clearly reveals the other focus, in their experiment, Manoharan et al. create an elliptical quantum corrall (see cover) in which the appearance of an atom at one focus of the ellipse is clearly mirrored at the other "empty" focus.

Hari Manoharan (Stanford),
Don Eigler (IBM),
and coworkers

news feature

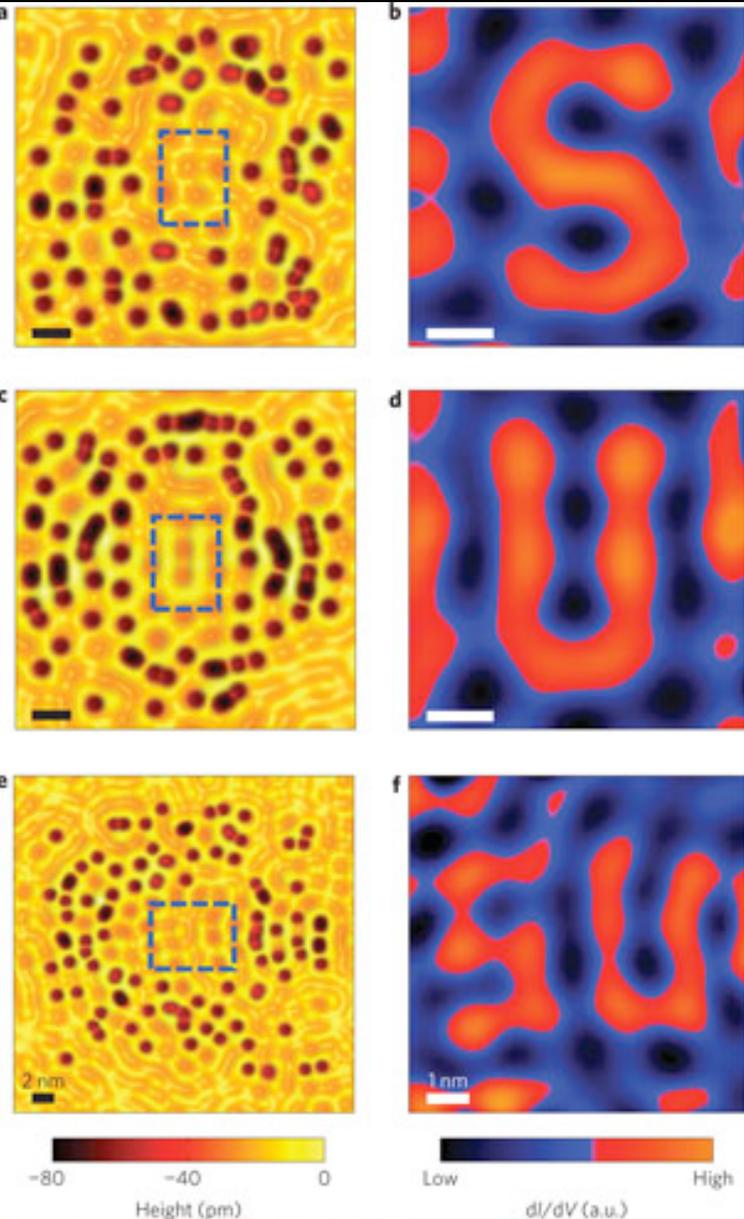
Nanotech thinks t

The science of the incredibly i anticipated influx of US govern interdisciplinary nanoscale res

There is no such thing as bad publicity, it is sometimes said. But ever since Eric Drexler brought the term "nanotechnology" into vogue in his 1986 book *Engines of Creation*, some researchers have felt that the field has been hindered by unrealistic hopes. Under constant media scrutiny, faculty positions have been required to self-replicating, nanoscale "assemblers" — self-replicating, nanoscale "assemblers" — humans to become the dominant life forms on any planet. These ideas were quickly set on by Transhumanists — people who imagine what the world will look like after technology has rendered us extinct.

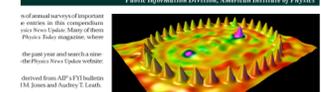
But today, nanotechnology is regaining the respect researchers in the field believe it deserves. This year for the first time, the US government has identified nanoscale science and technology as a top research priority. The European Union and other nations are contemplating similar actions, and bright young scientists and engineers are starting to gravitate toward the field. The intellectual drive is even more important than the funds at the moment," says Richard Bowen, senior technology program manager at the US National Science Foundation (NSF), and one of the major forces in pushing the field up the federal research agenda.

Back to basics
The US Congress has been asked to fund a new National Nanotechnology Initiative, which would double federal funding for the discipline to \$300 million in 2003. When President Bill Clinton launched the initiative



News In 1999

Edited by Phillip E. Schewe and Ben P. Stein
Public Information Division, American Institute of Physics



of actual arrays of superconducting qubits in this computer-generated image. (Image courtesy of the Physics Today magazine, where the past year and month is cited.)

derived from AP/STY/Edith 133 Jones and Aubrey L. Lewis

Small atoms in an elliptical disk of mercury. (Image courtesy of Hari Manoharan et al., Science, 285, 1999, 1485.)

Policy in 1999: The Year in Review

AUGUST

news and views
Electrons in the looking glass

Eric Heller

The scanning tunneling microscope (STM) is a marvel to scientists and the general public. Twenty years ago, individual atoms or "dots" had never been imaged, although they are two light years away from being photographed. As the electrons are sent moving in atomic and molecular orbitals, in textbook fashion.

The electrons make a surprising appearance on the condensed-matter physicist's turf in the form of conductance electrons freely moving around on the surface of metal, such as copper. Not only that, but at low temperatures they showed off their true quantum nature by creating dramatic interference patterns that can only happen when waves come together, adding crest to crest (constructive interference), or crest to trough (destructive interference). The STM images that emerged from Donald Eigler's laboratory are now well known, earning the cover page (right crown) of the covers of *Nature*, *Science*

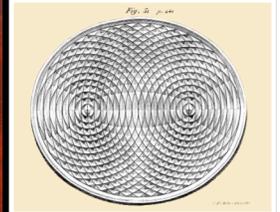


Figure 1: Wires in an elliptical disk of mercury. This drawing by the Miller brothers in 1825 may be one of the most remarkable hand-drawn scientific illustrations ever. It shows what happens when you put droplets of liquid mercury into one focus of an elliptical disk filled with mercury. The experiment clearly reveals the other focus, in this experiment, Manoharan et al. create an elliptical quantum corral (see cover) in which the appearance of an atom at one focus of the ellipse is clearly sensed at the other "empty" focus.

Hari Manoharan (Stanford), and coworkers



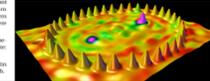
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The New York Times



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news fe

Nano

The science anticipates interdisciplinary

There is a sense of excitement in the field of nanotechnology. The science anticipates interdisciplinary work between physics, chemistry, biology, and engineering. The field has been expanding rapidly, and self-replicating structures are being built. Humans to be used as a platform for technology. The respect for science and technology. The European Union is concentrating young scientists. The National Science Foundation is upping the federal

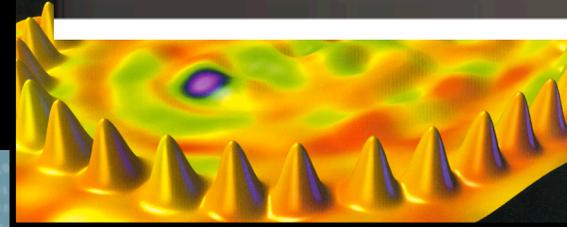
Back to basics

The US Congress has passed a new 'National Science Foundation' which would discipline to 15

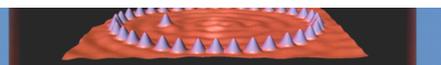
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En Español

THE TONIGHT SHOW WITH JAY LENO



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Directions in Information Technology

HE Center

Hari Manoharan (Stanford),
Don Eigler (IBM),
and coworkers



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Trends in Measurements at the Nanoscale

Thanks for discussions and slides:

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