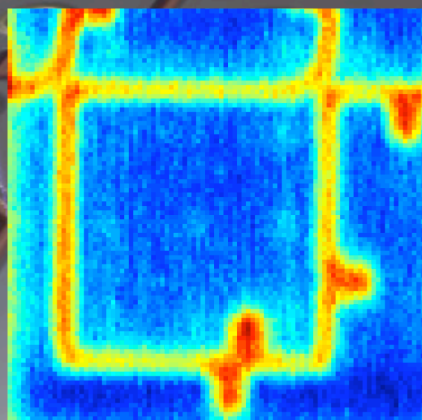
Trends in Measurements at the Nanoscale

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.

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

Current Trends in Measurements at the Nanoscale

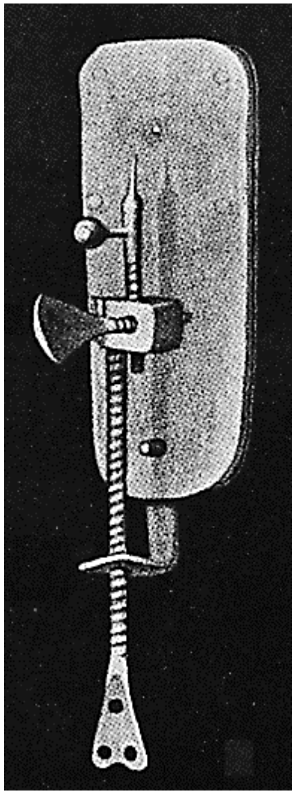
3-dimensional imaging

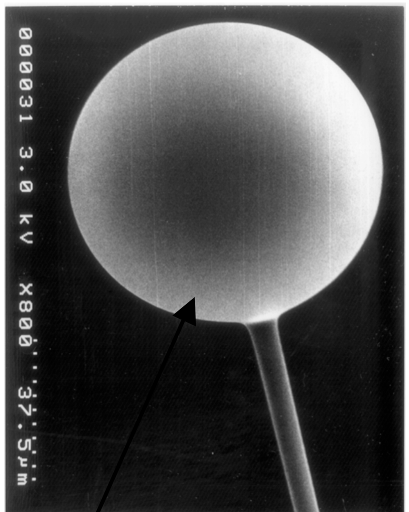
“3+1”-dimensional imaging: dramatically increased time resolution

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

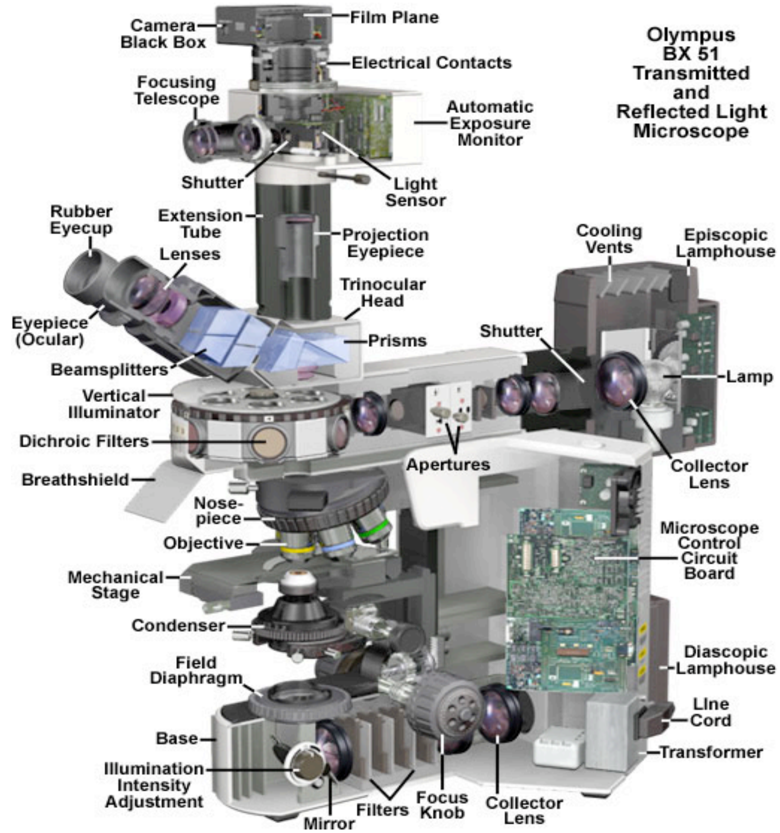
Optical microscopes

Van Leeuwenhoek's microscope (1673)





Modern microscope



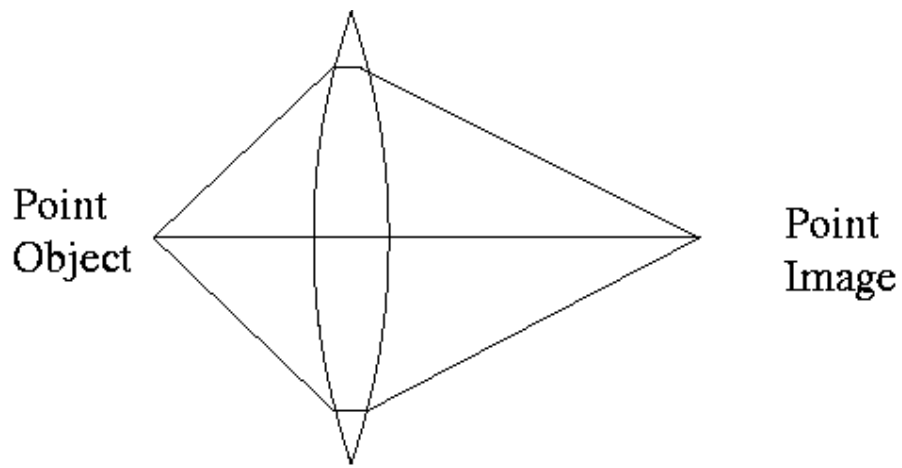
- Little glass sphere acted as a lens
- Discovered bacteria, blood cells, etc.

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

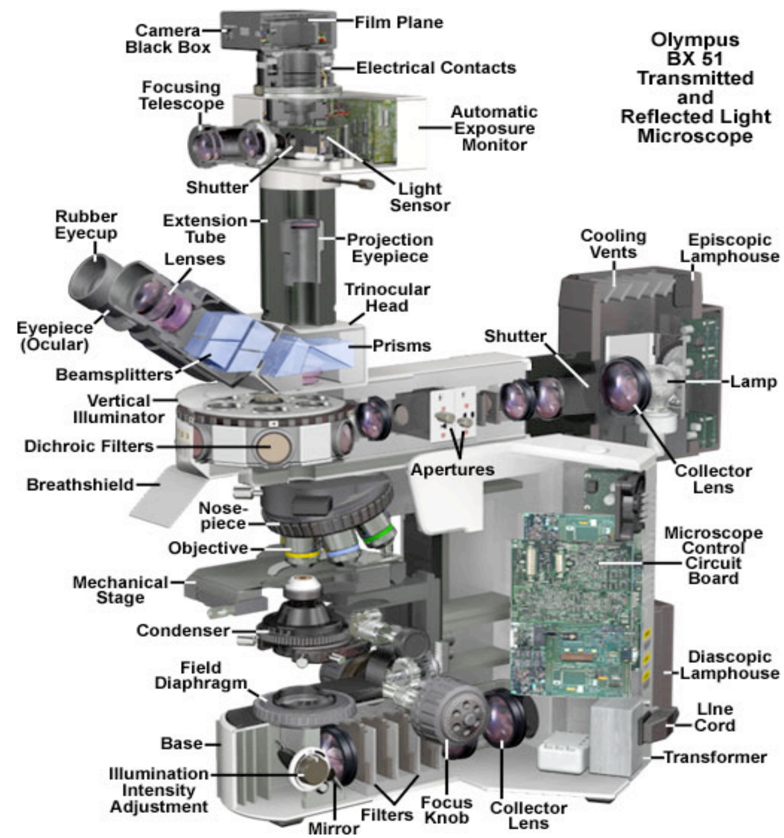
From: Mark Brongersma

Optical microscopes

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



Modern microscope

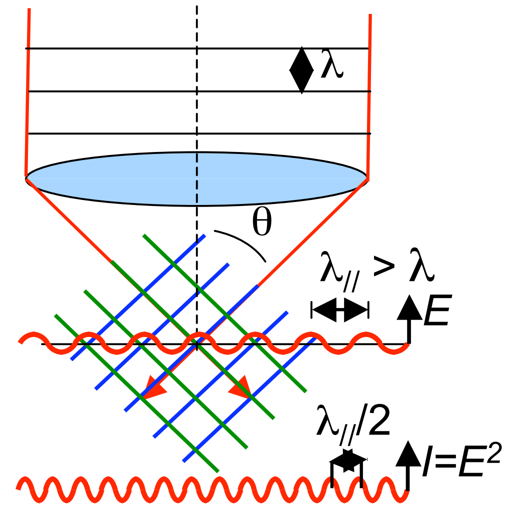


One of the most important tools to characterize materials (dead or alive!)

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 Δr ≈ **λ/2 ≈ 250 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
…

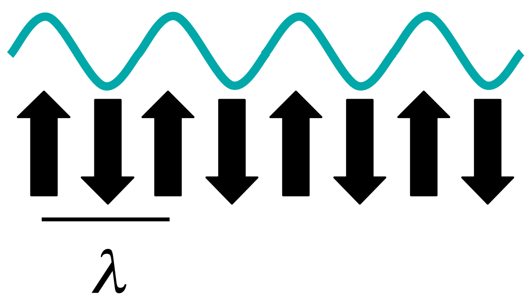
For many of these properties, we've always needed local sensors, even at the humanscale.

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

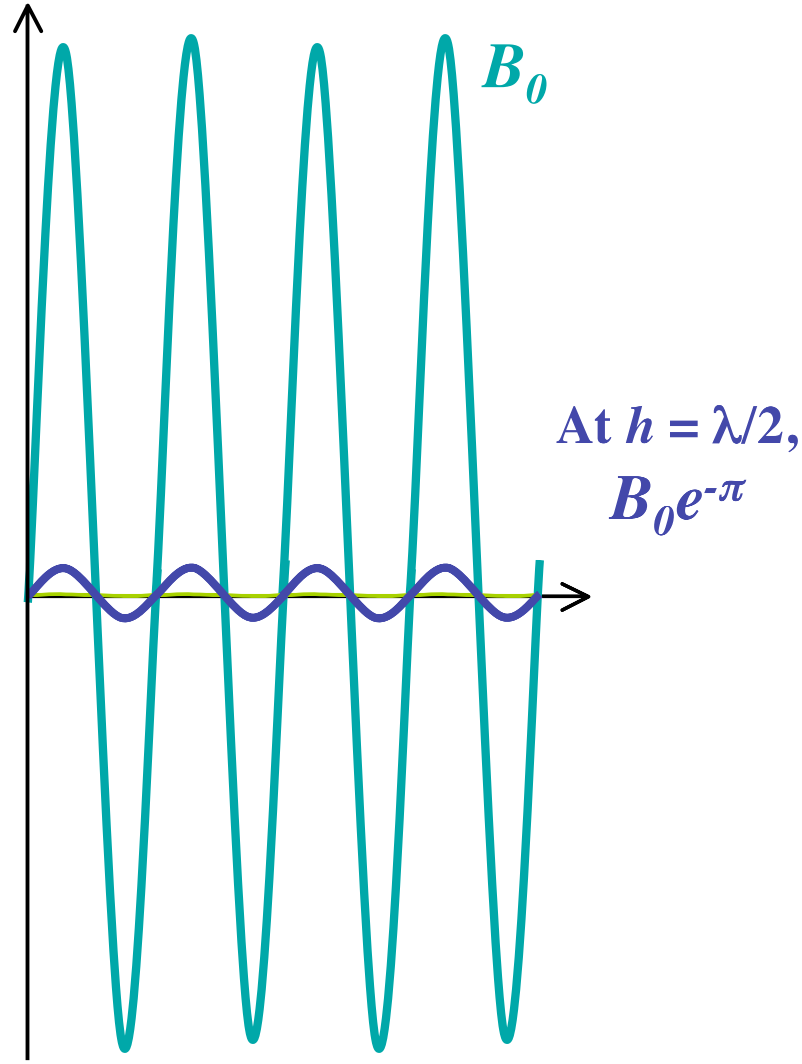
$$B_z(x, z = 0) = B_0 \cos(kx)$$



$$k = 2\pi/\lambda$$

Resulting magnetic field at a distance *h*

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



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

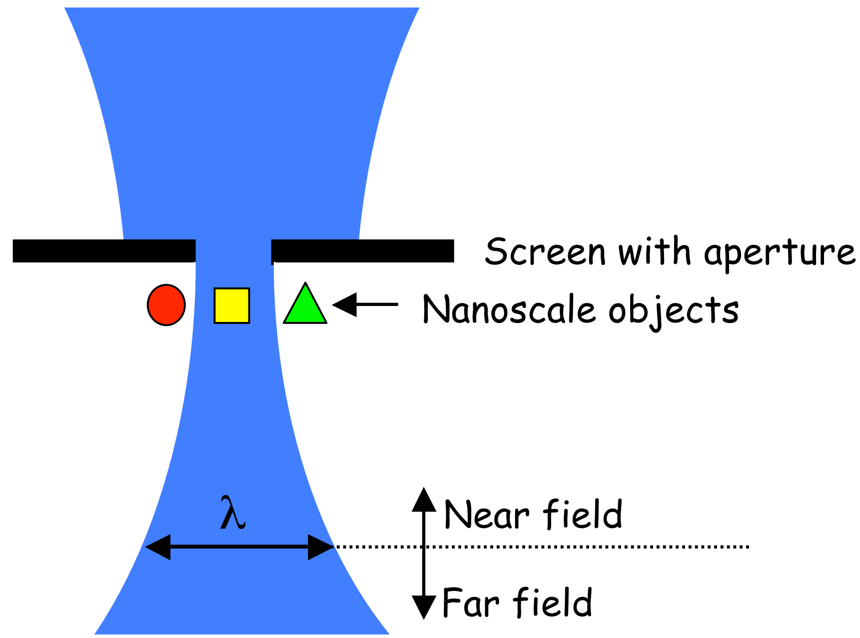


Image: Mark Brongersma

General considerations for nanosensors

spatial resolution
bandwidth
invasiveness
usability:
- fast turnaround
- accessibility

range of operable environments
quality of information:
- interpretability
- precision/sensitivy

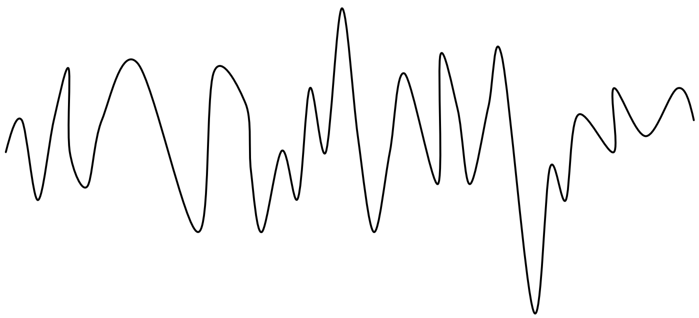
Signal-to-Noise at the Nanoscale

Less stuff
=> less signal

Fewer particles
=> more fluctuations
=> more noise

Quick Introduction to Noise Spectra

Time Trace y(t)



Fourier Transform

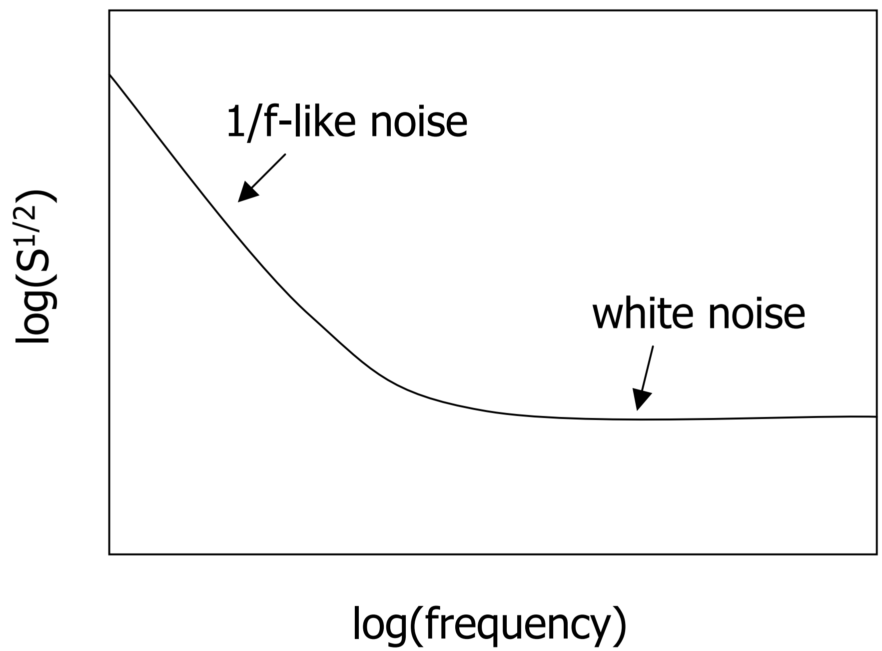
$$Y(f)$$

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/$Hz^{1/2}$

Minimum detectable signal (with S/N = 1) = $\dfrac{S^{1/2}}{\textit{Square root}\text{ of the measurement time}}$

Reason #2: we want time resolution!

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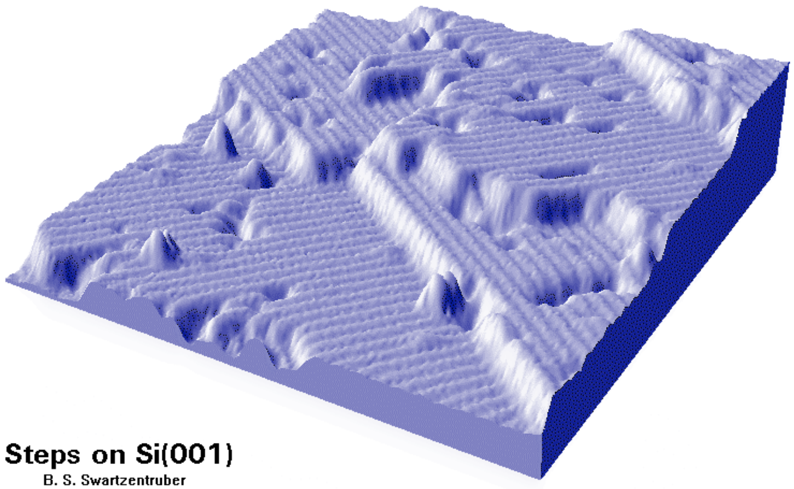
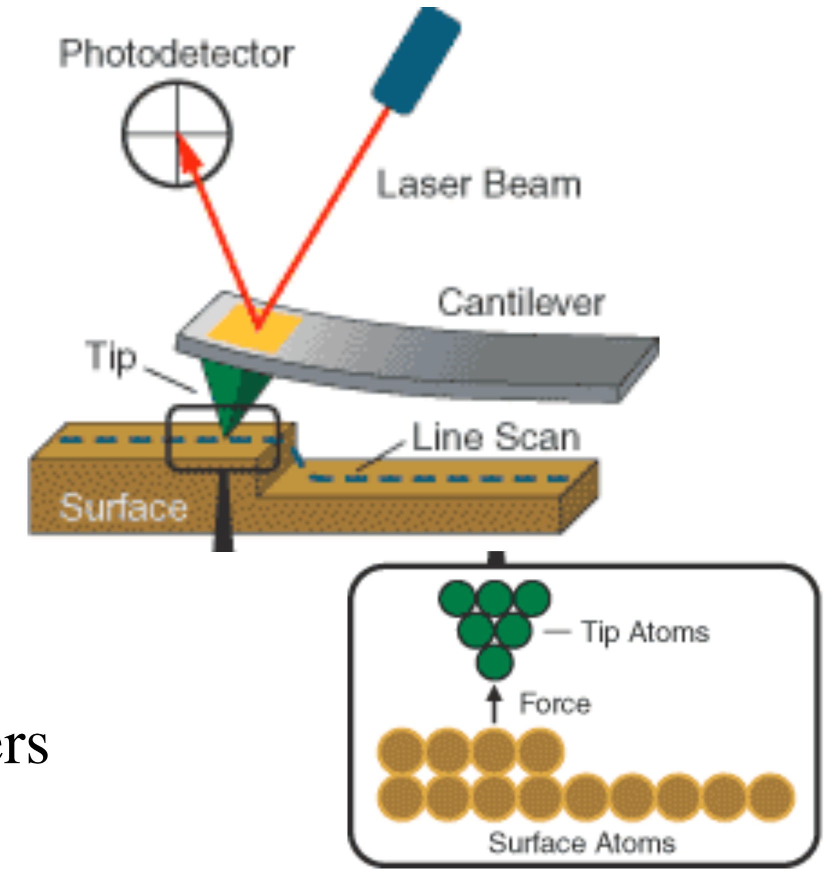
Increasingly good commercial tools are increasingly accessible

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



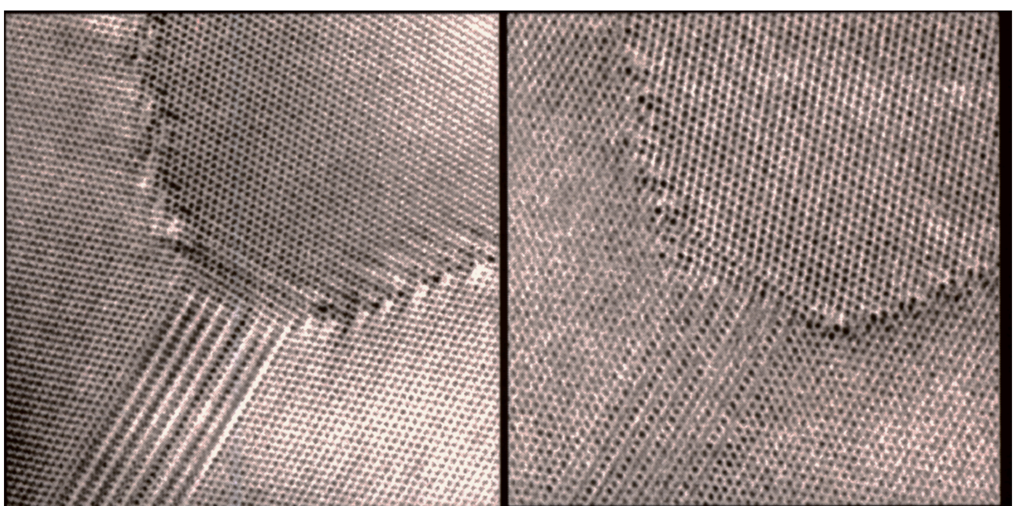


But…. many types of scanned probes remain inaccessible to many researchers

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

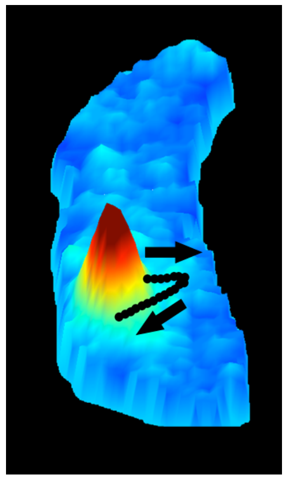


Specific trends in state-of-the-art measurement technologies

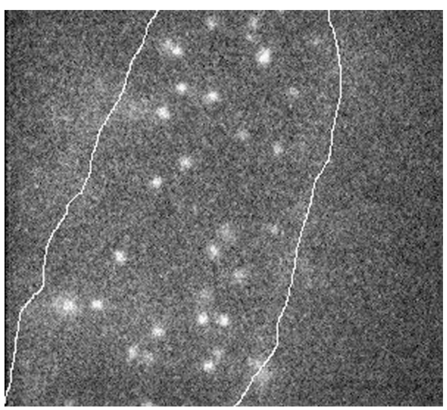
1. Increasingly good commercial tools are increasingly accessible
2. Clever techniques enable sub-wavelength, three-dimensional imaging, even in biological systems.

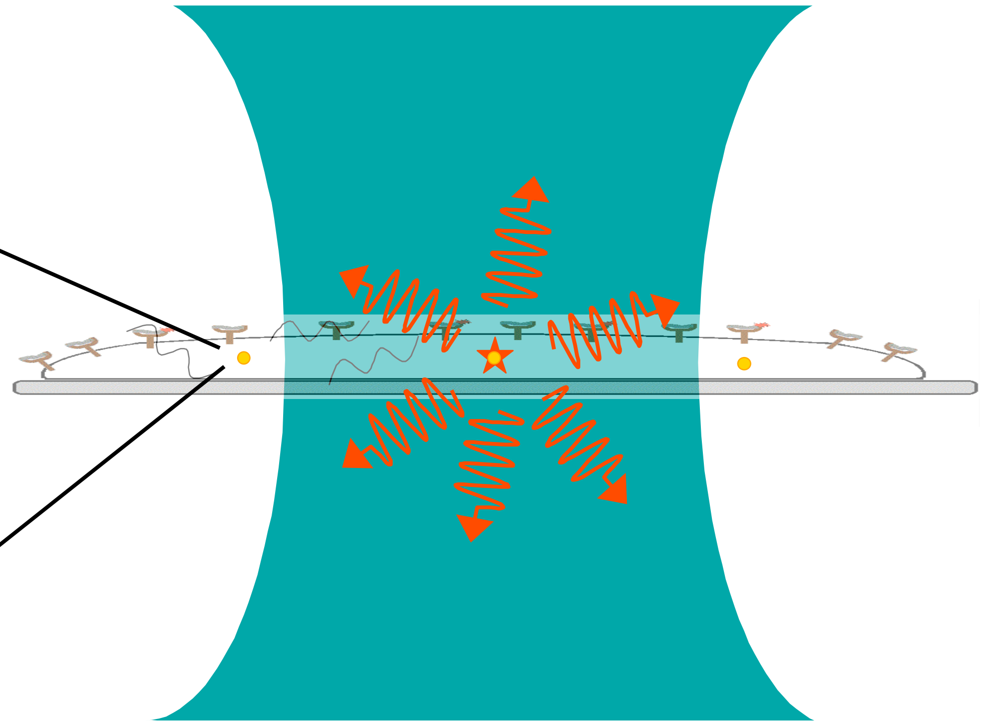
Visualizing Single Molecules in Living Cells
W. E. Moerner

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, Vrjlic et al. BPJ 2002, 2005
Protein binds peptides, peptides have fluorescent label.

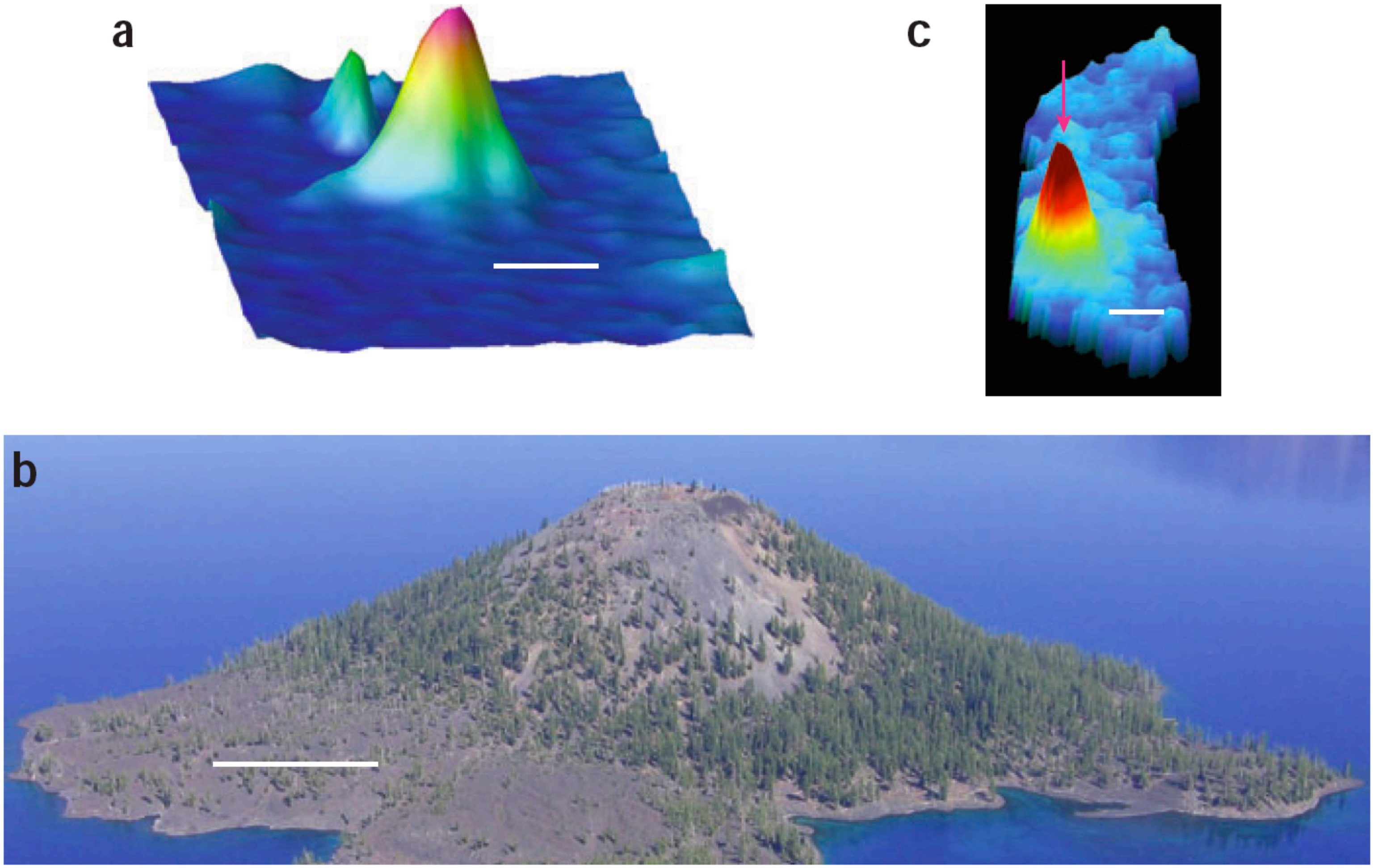


Figure 1 | Measuring mountain peaks for superresolution imaging. (**a**) Position-frequency image of single molecules of pentacene in a crystal[1], as a pumping laser beam is moved across the sample and the fluorescence is recorded. (**b**) It is easily possible to walk to the top of the cinder cone 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**, ~120×10^9 nm; **c**, 250 nm.

W.E. Moerner, Nature Methods, October 2006

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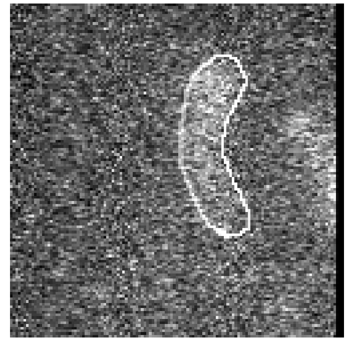
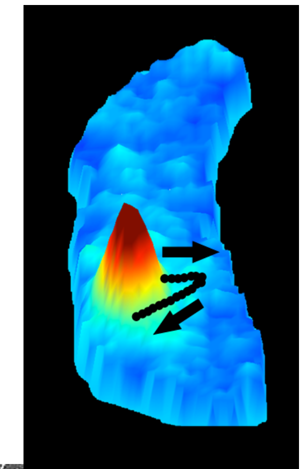
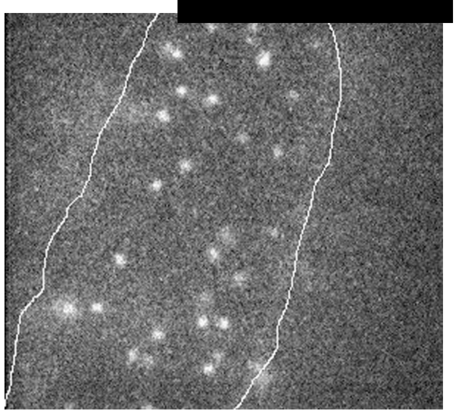
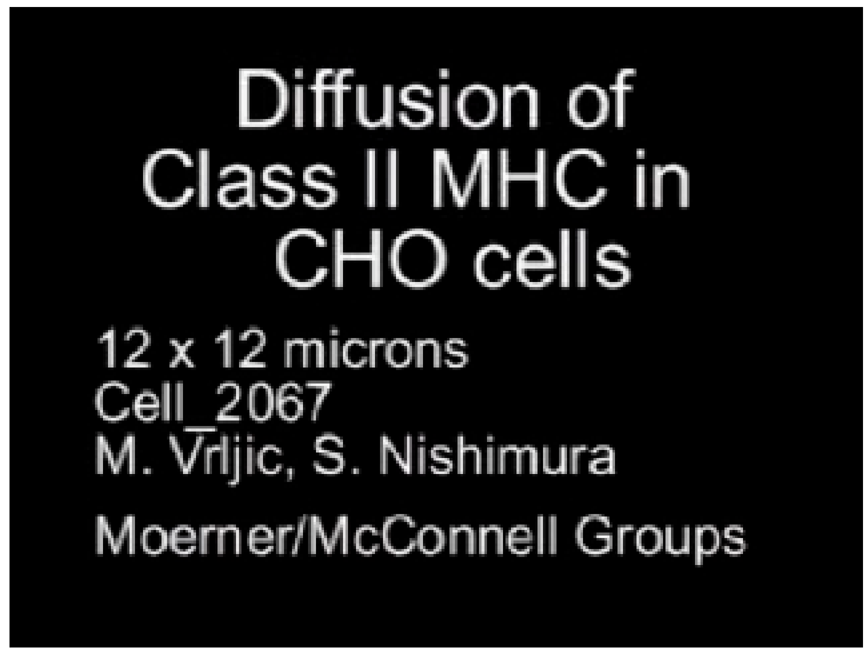




+/- 15 nm position resolution





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!

http://www.stanford.edu/group/moerner/sms_movies.html

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.

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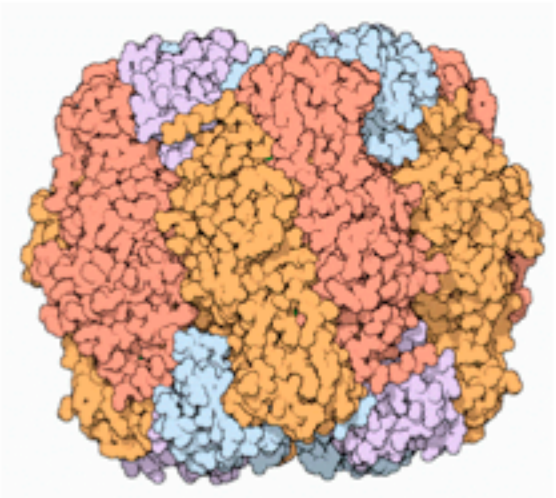
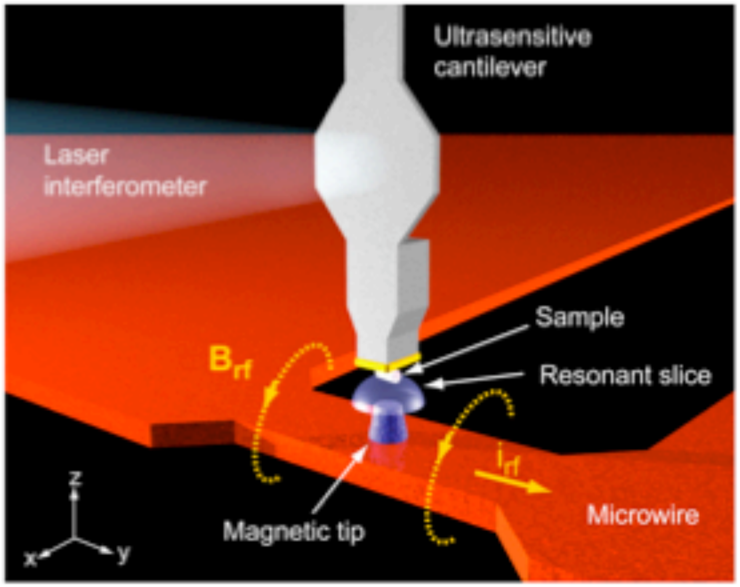
The Quest for a Molecular Structure Microscope

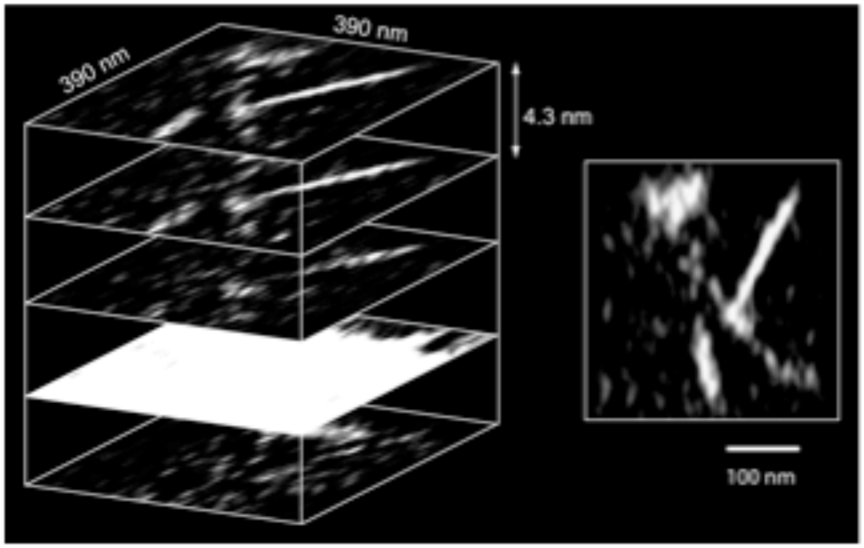


- Can a microscope be built that can directly image the 3D structure of molecules?
- Molecular structure is key to understanding biological structure and function
- Most proteins in your body have no known structure due to limitations of current techniques

Nanoscale MRI using a magnetic resonance force microscope



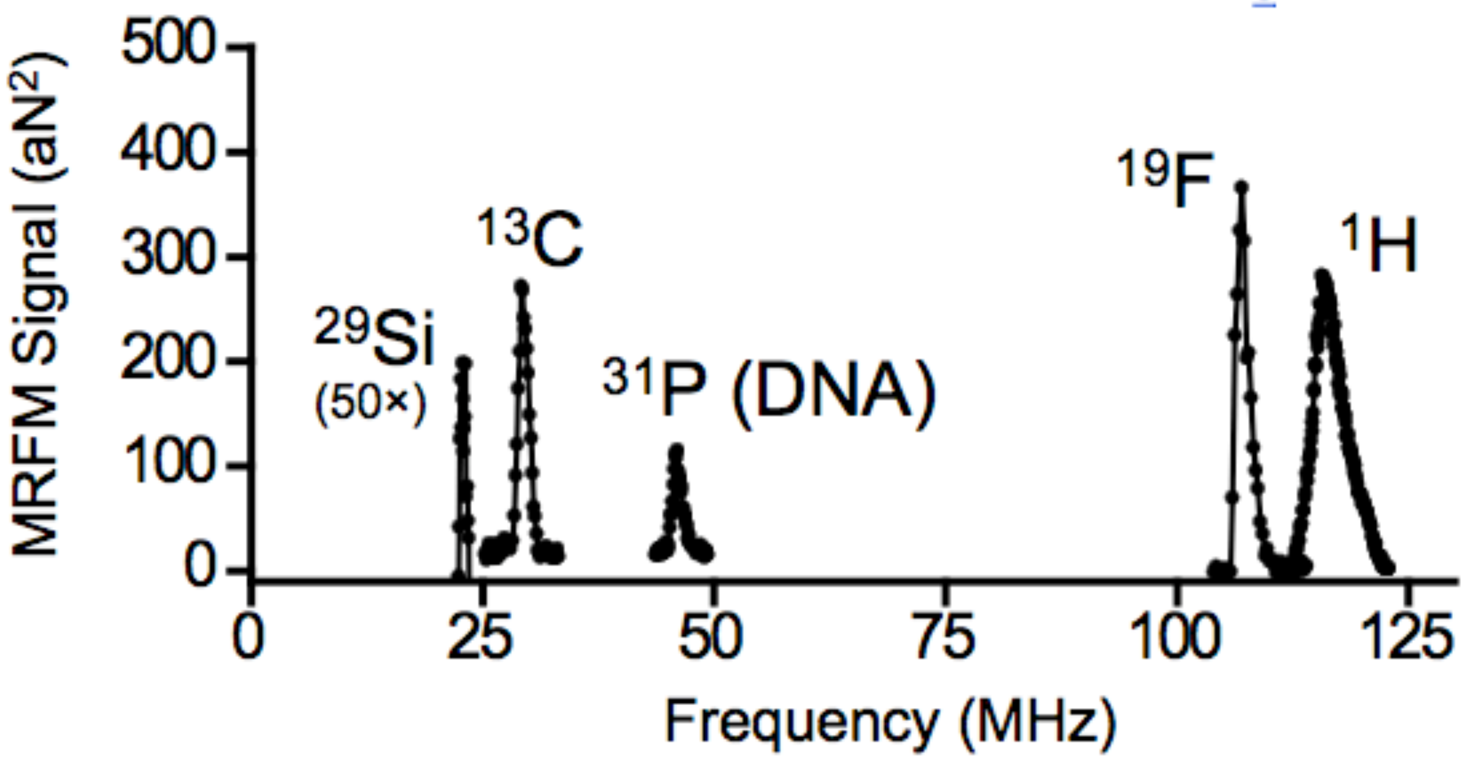
3D map of hydrogen nuclear spin density in virus particles



Elemental Selectivity of NMR-MRFM

Element	Gyromagnetic ratio
^{1}H	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 T



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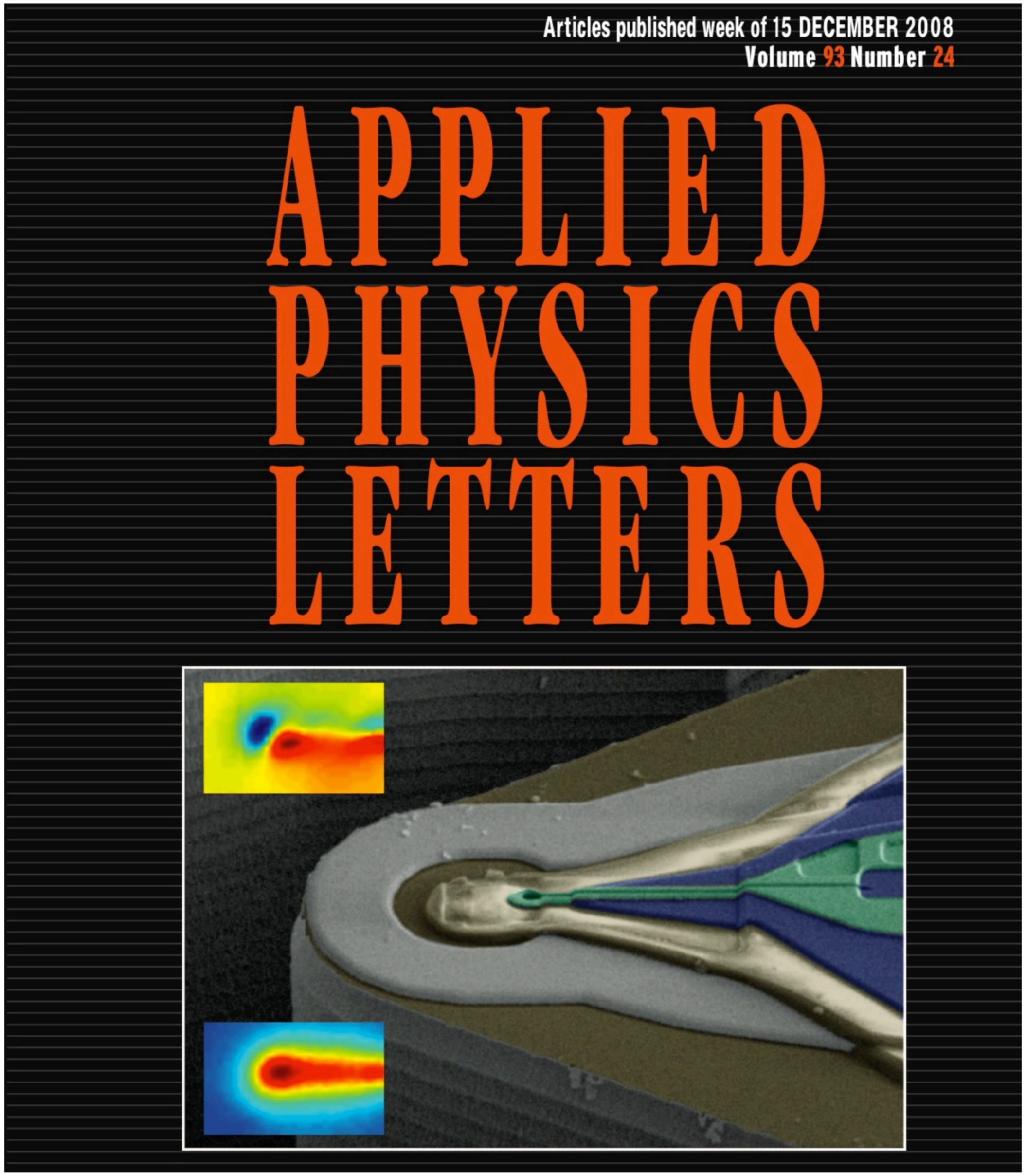
3. Magnetic Resonancy Force Microscopy: Magnetic Resonance Imaging is truly nano now
4. Advances in electronics and lasers allow “tabletop” time resolution, especially for periodic phenomena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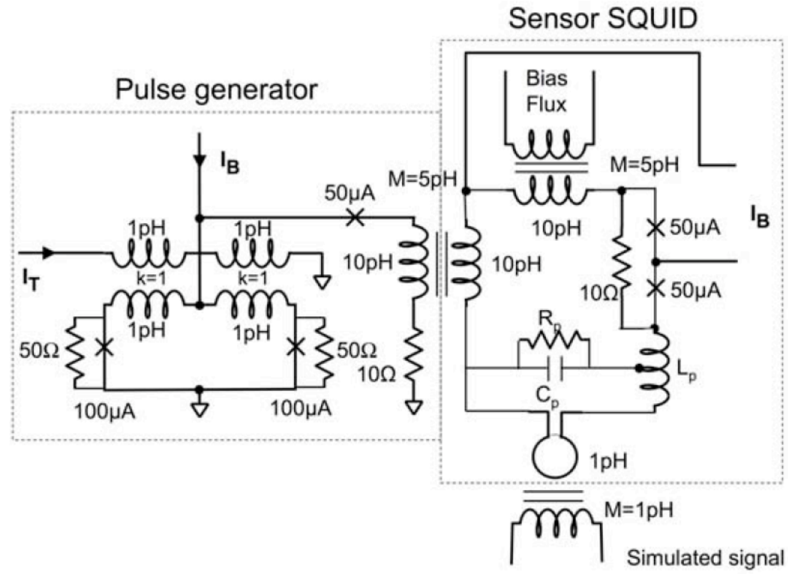
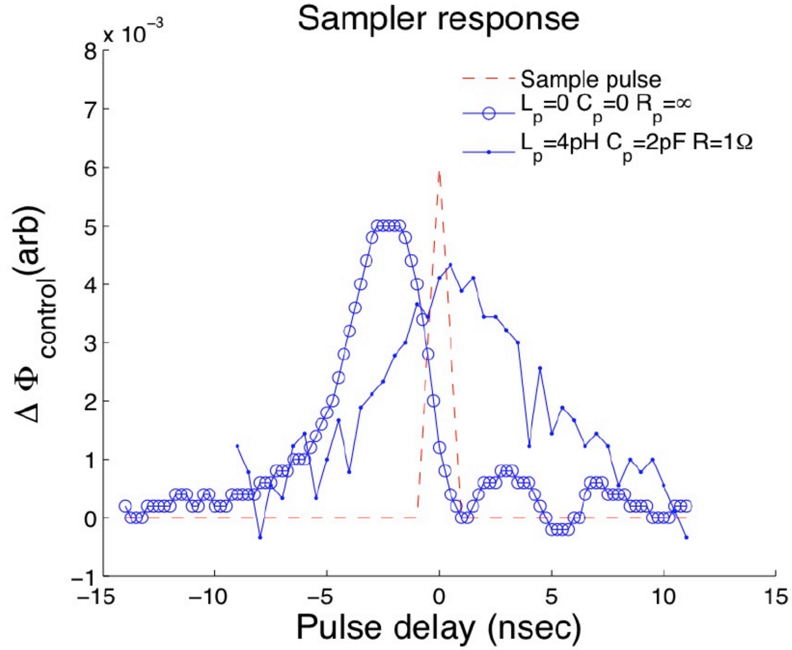
Volume 93 Number 24
APPLIED PHYSICS LETTERS


Sensor SQUID
Pulse generator
Bias
Flux
I_B
M=5pH
50μA
1pH
k=1
10pH
I_T
50Ω
10Ω
100μA
R_p
C_p
L_p
M=1pH
Simulated signal


Sampler response
x 10^{-3}
Sample pulse
L_p=0 C_p=0 R_p=∞
L_p=4pH C_p=2pF R=1Ω
$\Delta\ \Phi_{control}$(arb)
Pulse delay (nsec)

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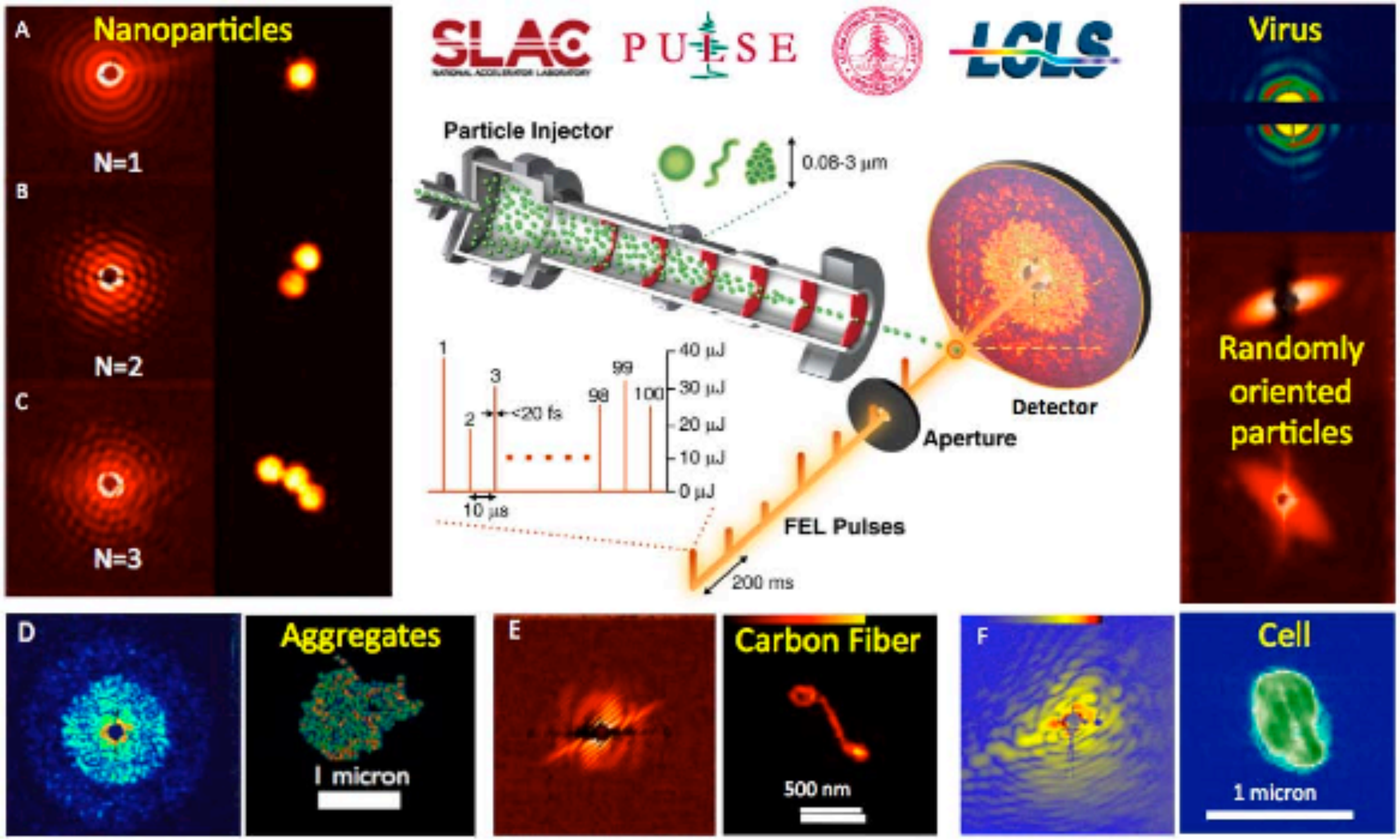
5. Unique accelerator-based fast, high-resolution imaging capabilities.

Nonperiodic Imaging

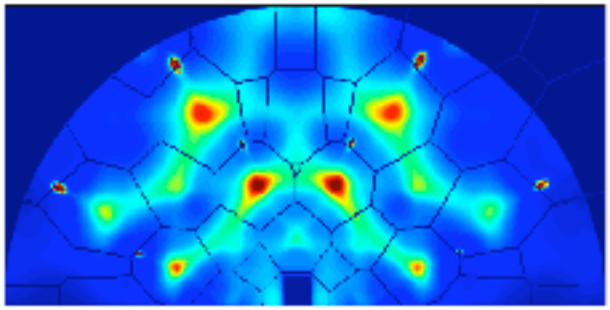


Nonperiodic nanoscale imaging at LCLS involves reconstructing x-ray scattering data from single nanoparticles. The frontier science questions under study range from nanobiology to aerosol chemistry to combustion

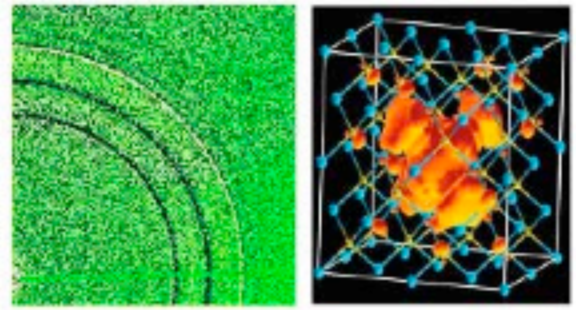
Nonequilibrium Dynamics in Solids

PULSE

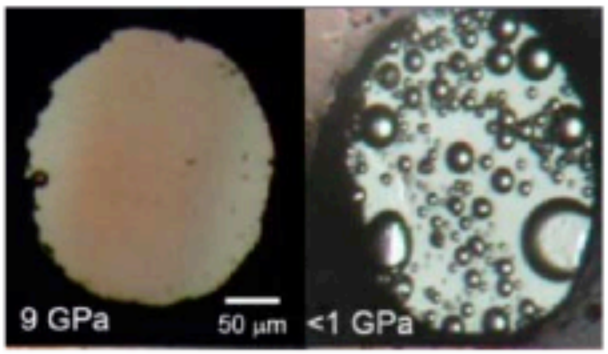
Nonequilibrium Phonon Dynamics



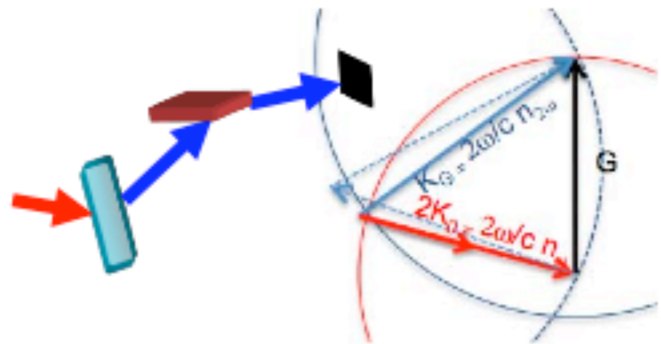
Nanoscale Phase Transitions



X-ray Modification of Materials



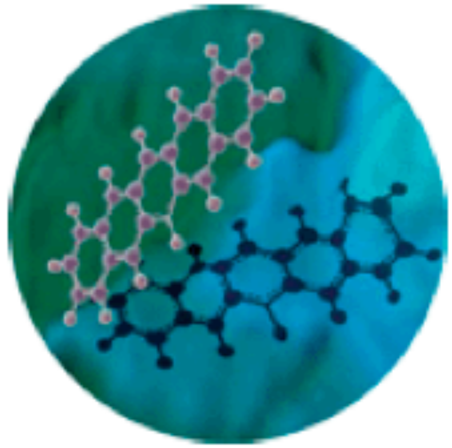
X-ray Nonlinear Optics



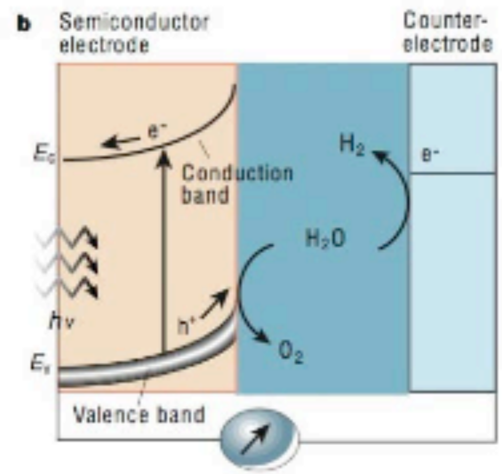
Ultrafast x-rays can track nonequilibrium dynamics in solids with atomic-scale resolution in time and space and with atomic specificity. LCLS is a unique tool for these studies.

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.

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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 F. Schewe and Ben P. Stein
Science Policy in 1999: The Year in Review
news feature
Nanotech thinks big
The science of the incredibly small is shedding its sci-fi image. An anticipated influx of US government funds is nurturing a new wave of interdisciplinary nanoscale research, says Colin Macilwain.
The New York Times
THE NEW YORK TIMES NATIONAL THURSDAY, FEBRUARY 3, 2000
Peeking at an Atom in a Hall of Mirrors
By GEORGE JOHNSON
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.
FOCUS A
FOCUS B
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.
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NewScientist
Escape to Mir!
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The selfish group
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The fossil record As good as it's long
IBM
Journal of Research and Development
Directions in Information Technology
Hari Manoharan (Stanford),
Don Eigler (IBM),
and coworkers

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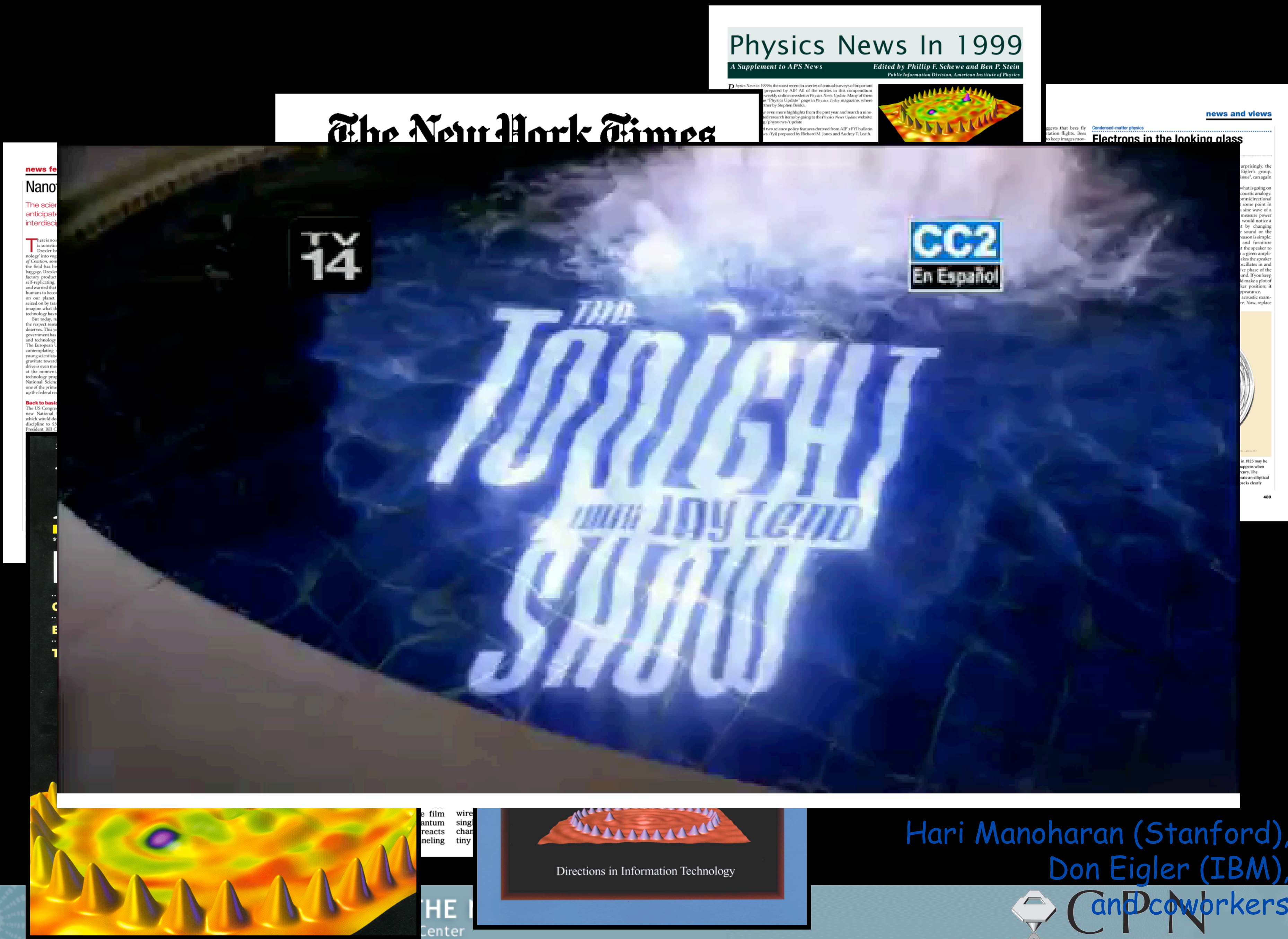

Hari Manoharan (Stanford),
Don Eigler (IBM),
and coworkers

Trends in Measurements at the Nanoscale

Thanks for discussions and slides:

Tobi Beetz

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Nick Koshnick

Hari Manoharan

W.E. Moerner

Dan Rugar