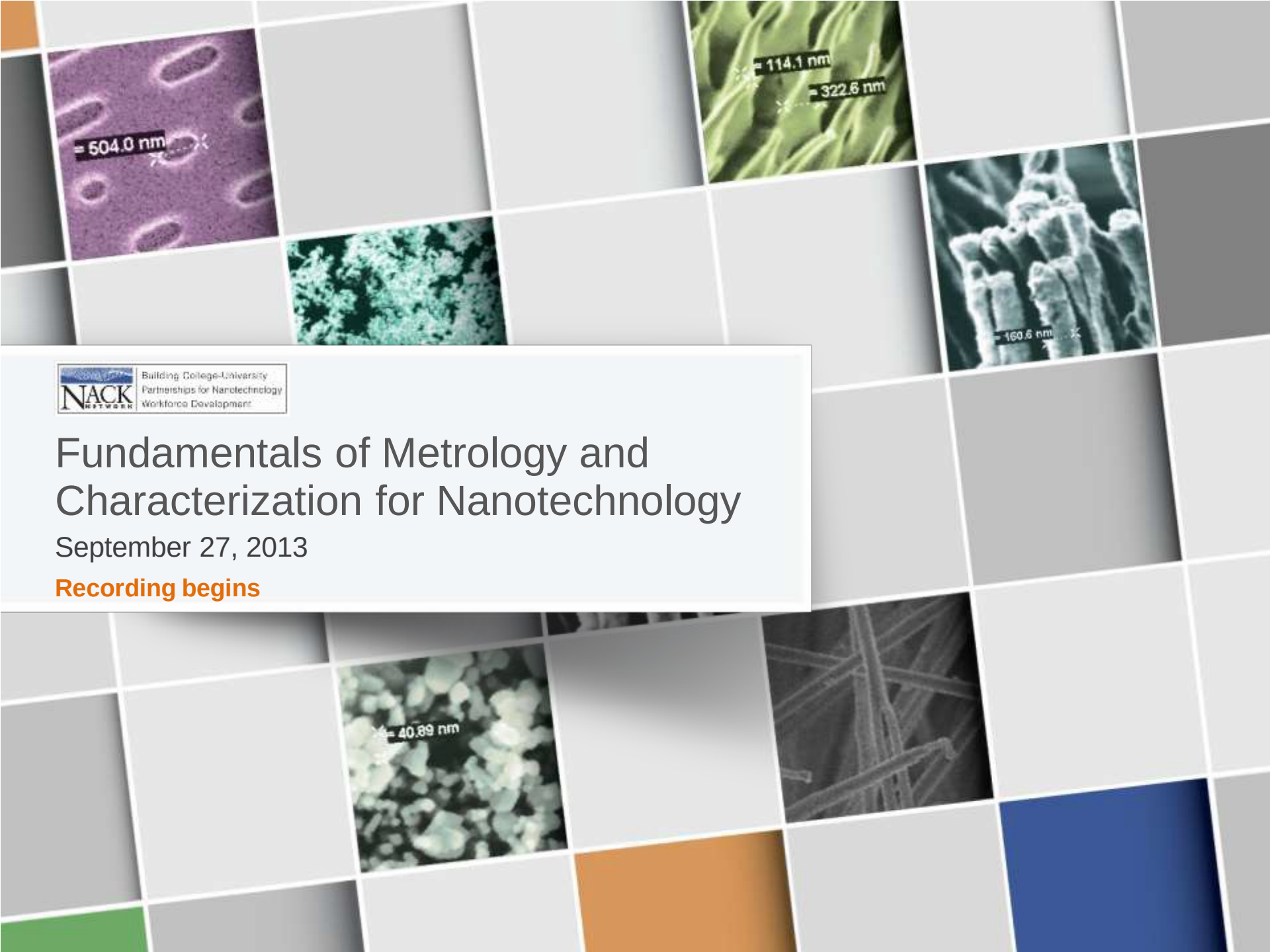


NACK NETWORK
Building College-University Partnerships for Nanotechnology Workforce Development

# Fundamentals of Metrology and Characterization for Nanotechnology

September 27, 2013

**Recording begins**

# Brought to you by:

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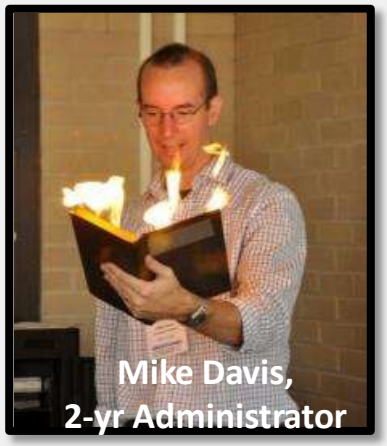
The NACK Network, established at the Pennsylvania State College of Engineering, and funded in part by a grant from the National Science Foundation.



Hosted by MATEC NetWorks ***www.matecnetworks.org***

# Welcome to NACK's Webinar

**Today's Presenter:**
Dr. Diane Hickey-Davis
Ph.D., Industry
NanoScience Instruments


Moderator: Mike Lesiecki

MATEC

MARICOPA COMMUNITY COLLEGES

# In today's webinar:

- How do we see what we can't see?
- Five **common** nanotech instruments
- For each, I'll cover:
  - **What** it does
  - **How** it works
  - Where it's used in **Industry**
  - What **subjects** you can teach with it
  - What **skills** your students can learn from it

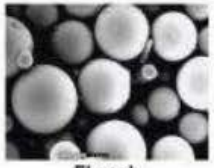
# The Scale of Things – Nanometers and More

## Things Natural

Dust mite
200 μm

Ant
~ 5 mm

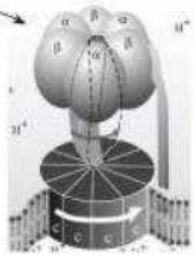
Human hair
~ 60-120 μm wide



Fly ash
~ 10-20 μm

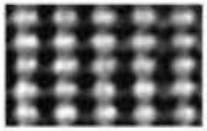
Red blood cells
(~7-8 μm)

~10 nm diameter

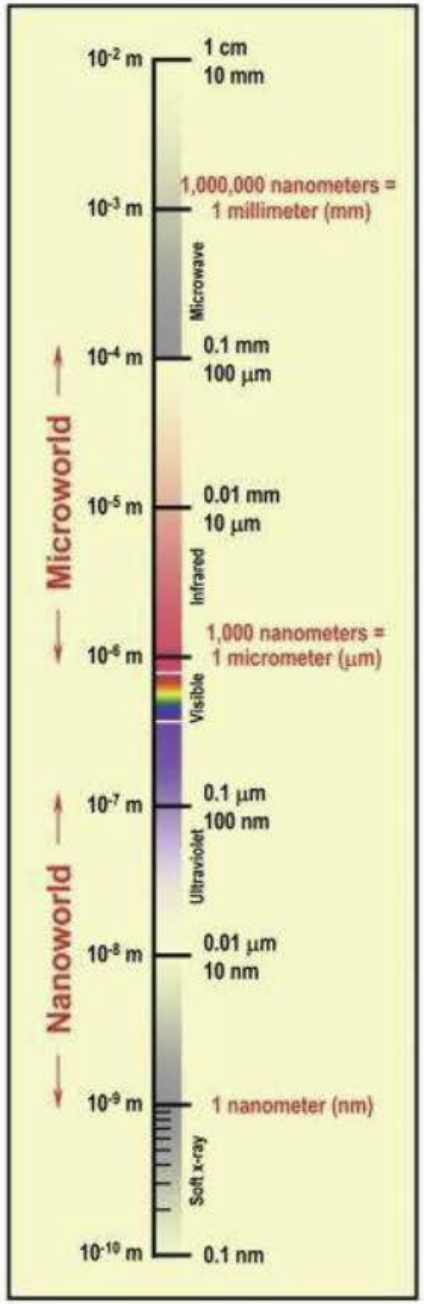


ATP synthase

DNA
~2-1/2 nm diameter

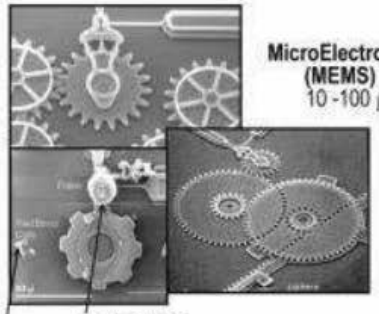


Atoms of silicon
spacing 0.078 nm



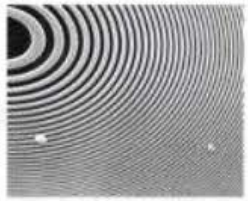

## Things Manmade

Head of a pin
1-2 mm

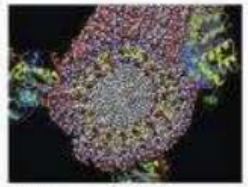


MicroElectroMechanical (MEMS) devices
10 -100 μm wide

Pollen grain
Red blood cells

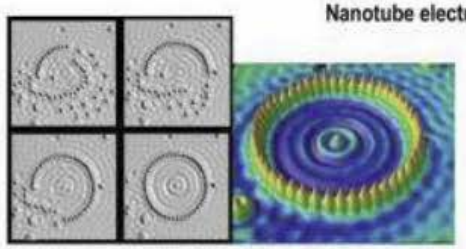


Zone plate x-ray "lens"
Outer ring spacing ~35 nm

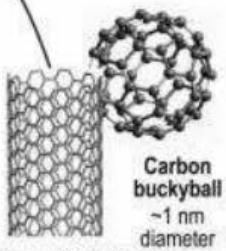


Self-assembled,
Nature-inspired structure
Many 10s of nm


Nanotube electrode



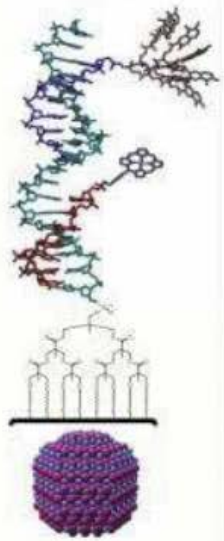
Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip
Corral diameter 14 nm



Carbon buckyball
~1 nm diameter

Carbon nanotube
~1.3 nm diameter

### The Challenge

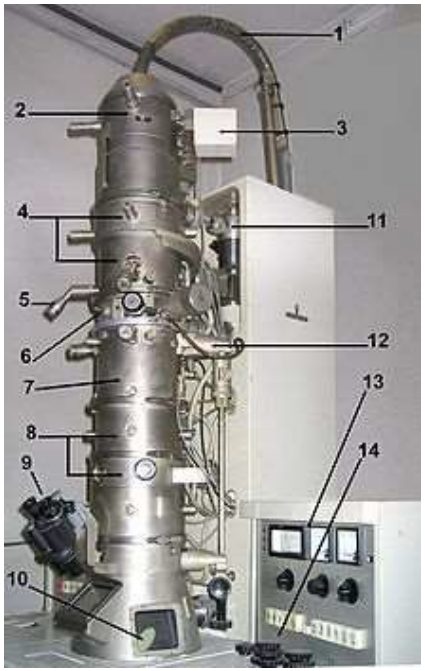


*Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.*

Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06.ppt

# Common fears about instruments

- What is it **used** for?
  - [industry]
- Would it be useful for my students to **learn**?
  - [educational benefit]



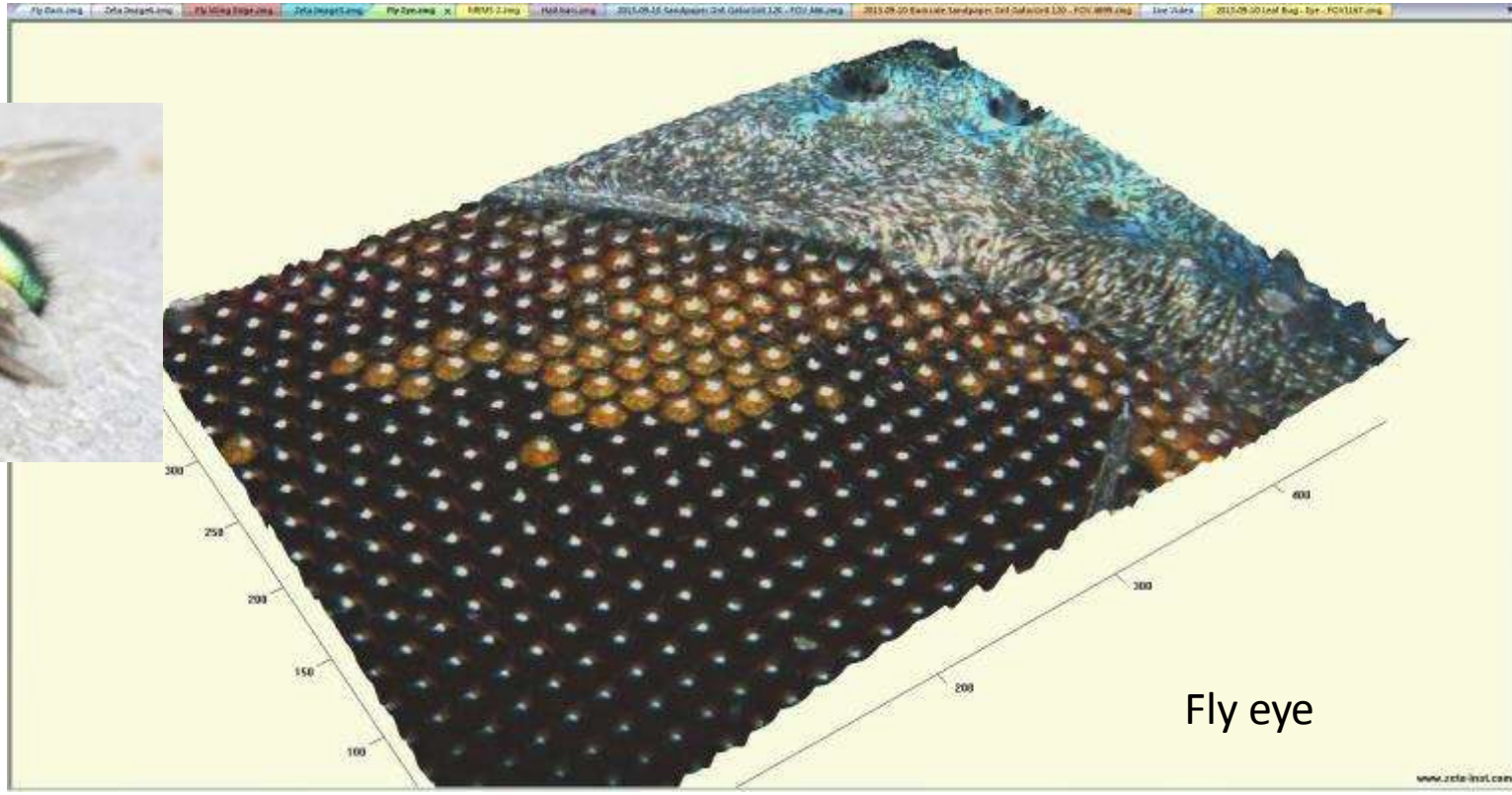

- **What do I do with it** once I've got it?
  - [content]
- Will it collect **dust**?
  - [45 min class period; too complicated?; needs expensive replacement parts?]

# Today: Alleviate Fears and Provide Info

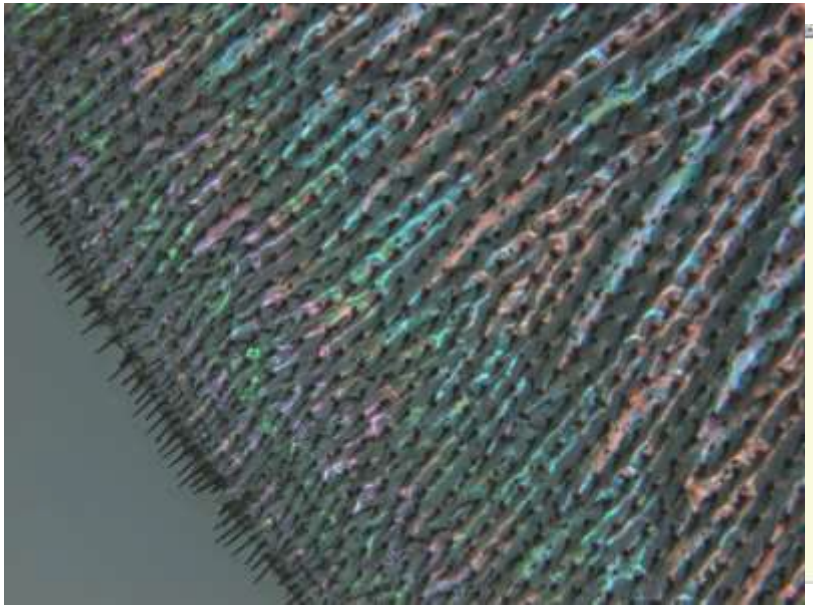
With each instrument, I'll try to communicate:

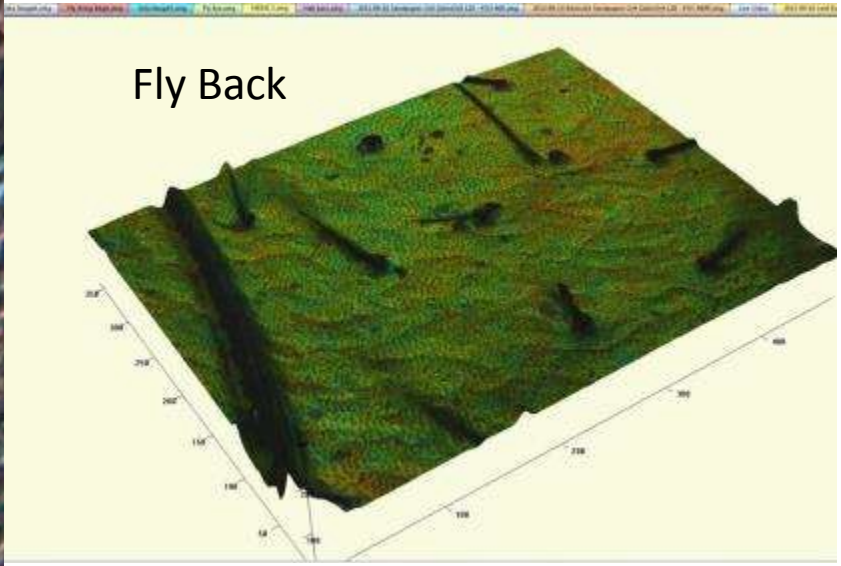
- What it **does**.
- How it **works**, on a high level.
- **Where** it's used.
- What **subjects** can be taught with it.
- What skills your students can **learn** from it. *(this is subjective)*

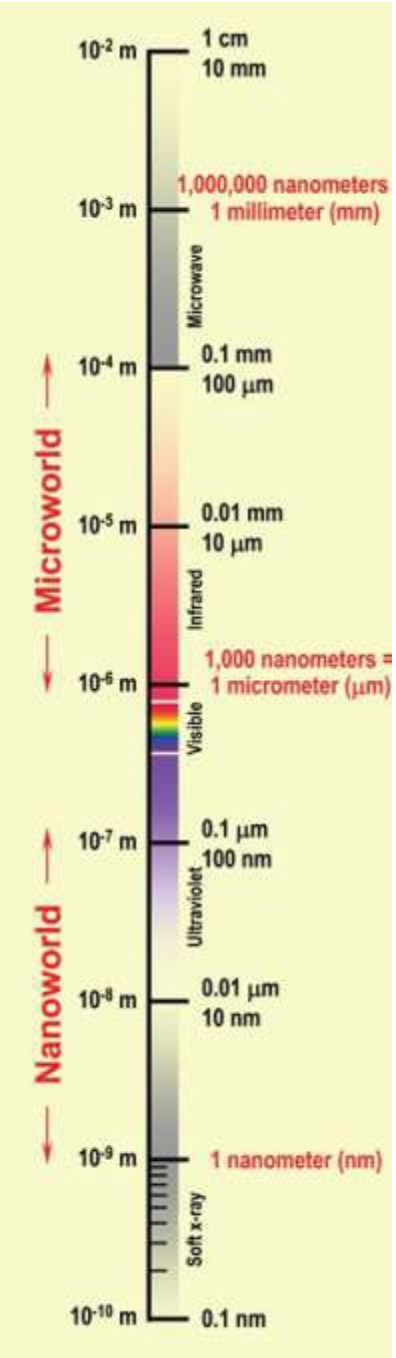
# Optical 3D Microscope




Fly Wing - Edge







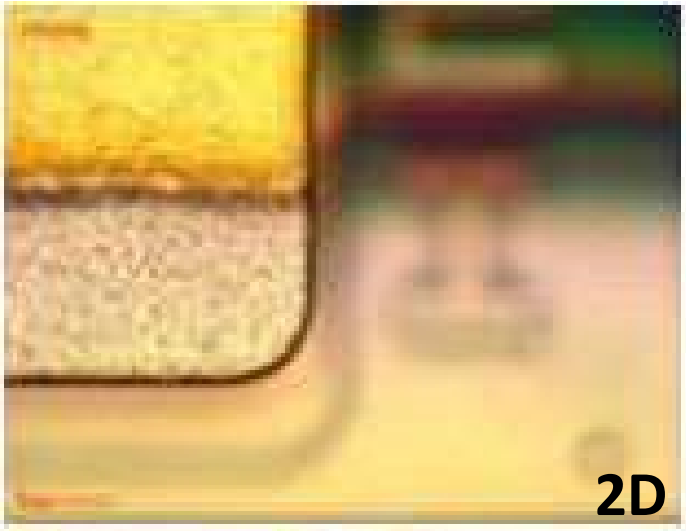

# Optical Microscope

Optical microscopy is ubiquitous in almost any scientific, medical or manufacturing quality environment.

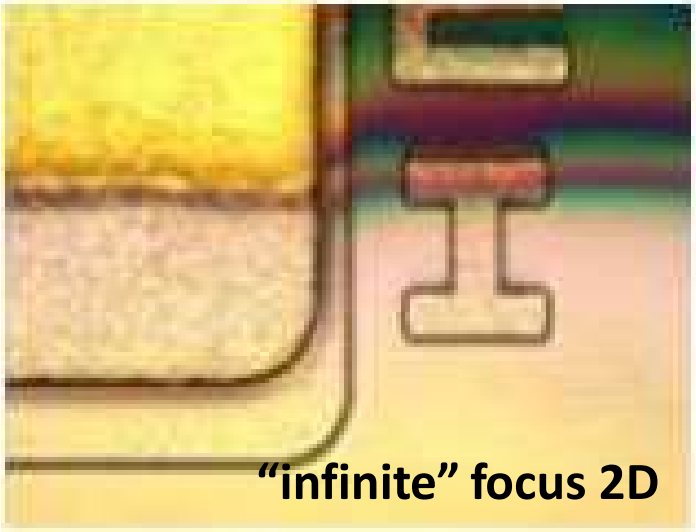
- **What does it do?**
  - It adds a third dimension (3D) to viewing samples, and adds quantitative measurement data.
- **How does it work?**
  - Taking 'slices' of optical images, it reconstructs the focal planes into a 3D image.
- **Where is it used?**
  - Industries: Semiconductor, Manufacturing, Medical devices.
  - Areas: Quality Control, Quality Assurance, Engineering design, Failure Analysis, etc.
- **What subjects can be taught with it?**
  - Integrates easily with Biology, Earth sciences, and the description of the optics for physics.
- **What skills can be taught?**

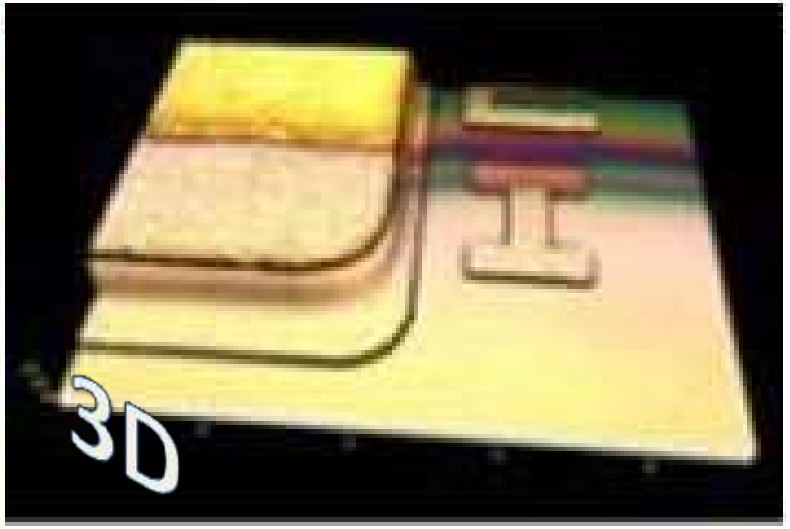
Optical metrology is widely used in:

- **high-tech manufacturing**,
- **quality control**, and
- **failure analysis.**



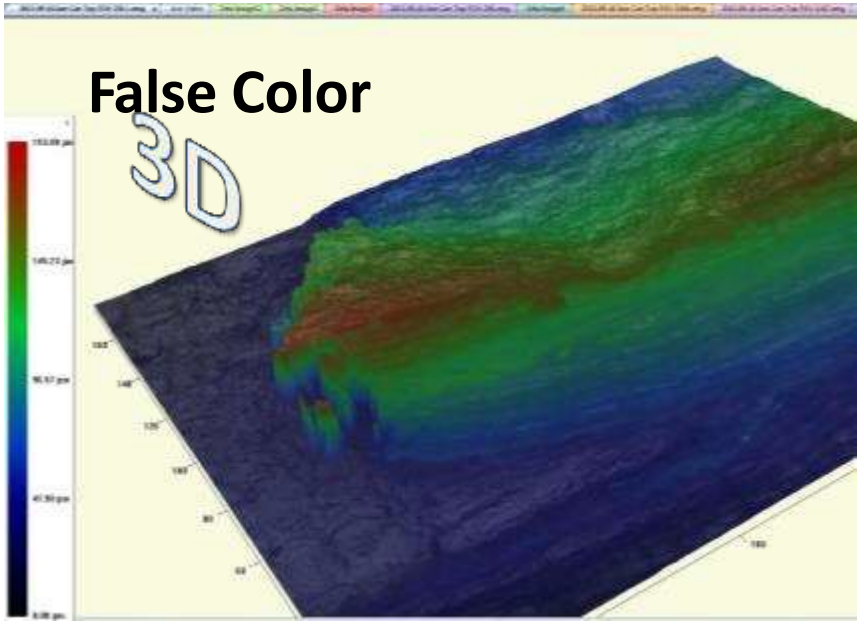

# A 3rd Dimension for Microscopy

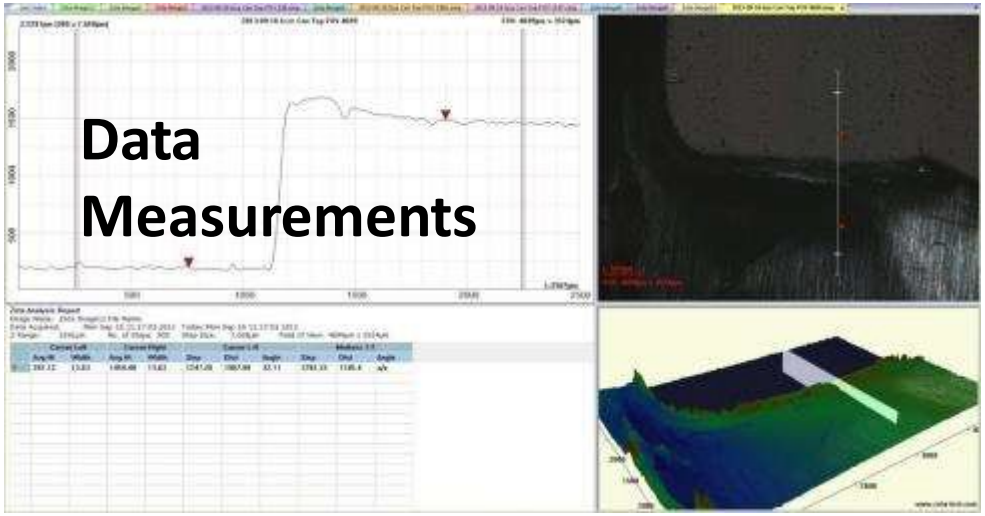


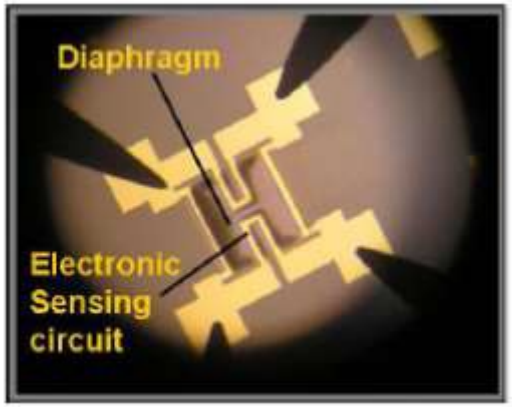
# Failure Analysis – Metal Parts

# Failure Analysis – Metal Parts

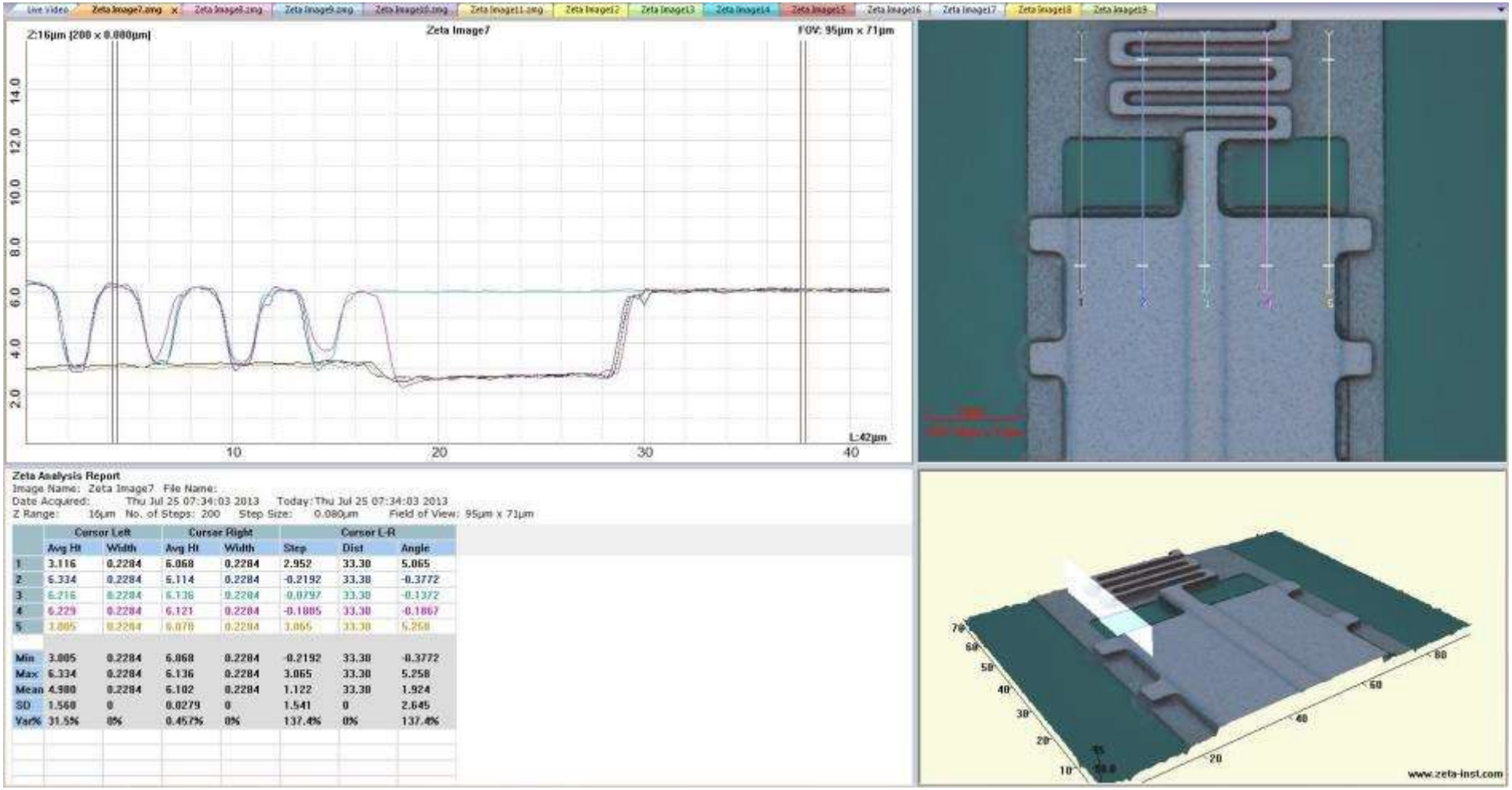



# Failure Analysis – Semiconductor Parts

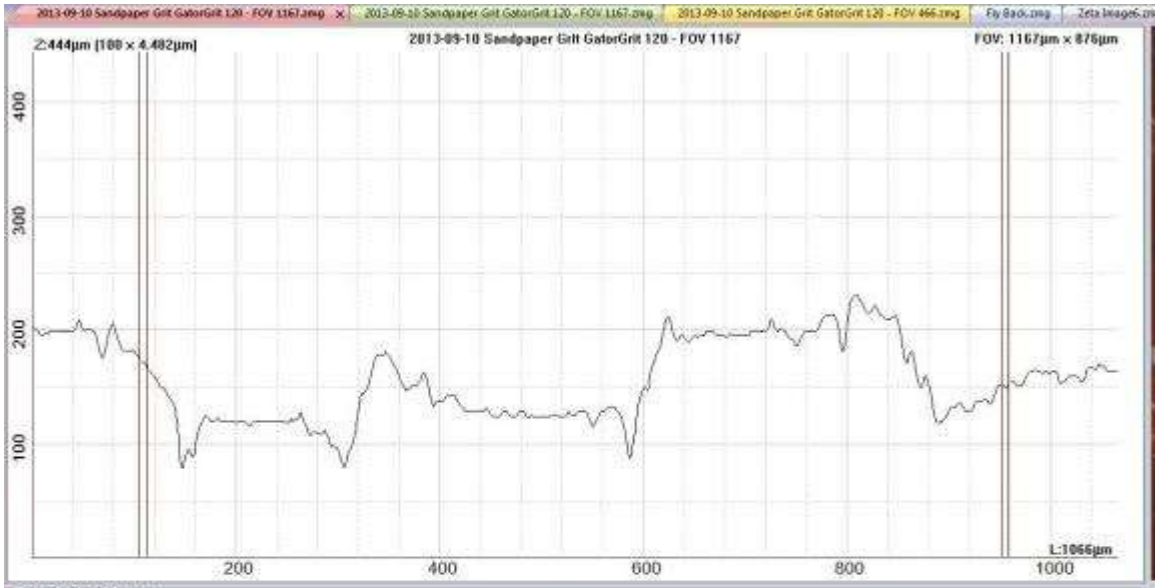



# MEMS Fabrication – Argonne National Lab

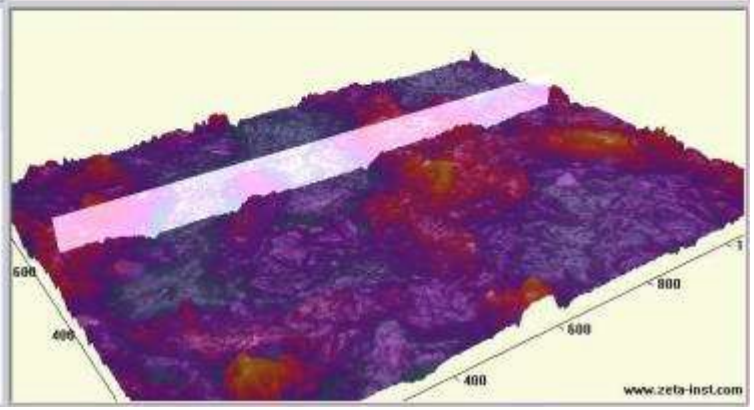



| | Cursor Left | | Cursor Right | | Cursor L-R | | |
|---|---|---|---|---|---|---|---|
| | Avg Ht | Width | Avg Ht | Width | Step | Dist | Angle |
| 1 | 3.116 | 0.2284 | 6.068 | 0.2284 | 2.952 | 33.30 | 5.065 |
| 2 | 6.334 | 0.2284 | 6.114 | 0.2284 | -0.2192 | 33.30 | -0.3772 |
| 3 | 6.216 | 0.2284 | 6.136 | 0.2284 | -0.0797 | 33.30 | -0.1372 |
| 4 | 6.229 | 0.2284 | 6.121 | 0.2284 | -0.1085 | 33.30 | -0.1867 |
| 5 | 3.065 | 0.2284 | 6.078 | 0.2284 | 1.066 | 33.30 | 5.258 |
| Min | 3.065 | 0.2284 | 6.068 | 0.2284 | -0.2192 | 33.30 | -0.3772 |
| Max | 6.334 | 0.2284 | 6.136 | 0.2284 | 3.065 | 33.30 | 5.258 |
| Mean | 4.980 | 0.2284 | 6.102 | 0.2284 | 1.122 | 33.30 | 1.924 |
| SD | 1.568 | 0 | 0.0279 | 0 | 1.541 | 0 | 2.645 |
| Var% | 31.5% | 0% | 0.457% | 0% | 137.4% | 0% | 137.4% |

# Companies like 3M use 3D Optical Profilers for Quality Control and/or R&D of Sandpaper



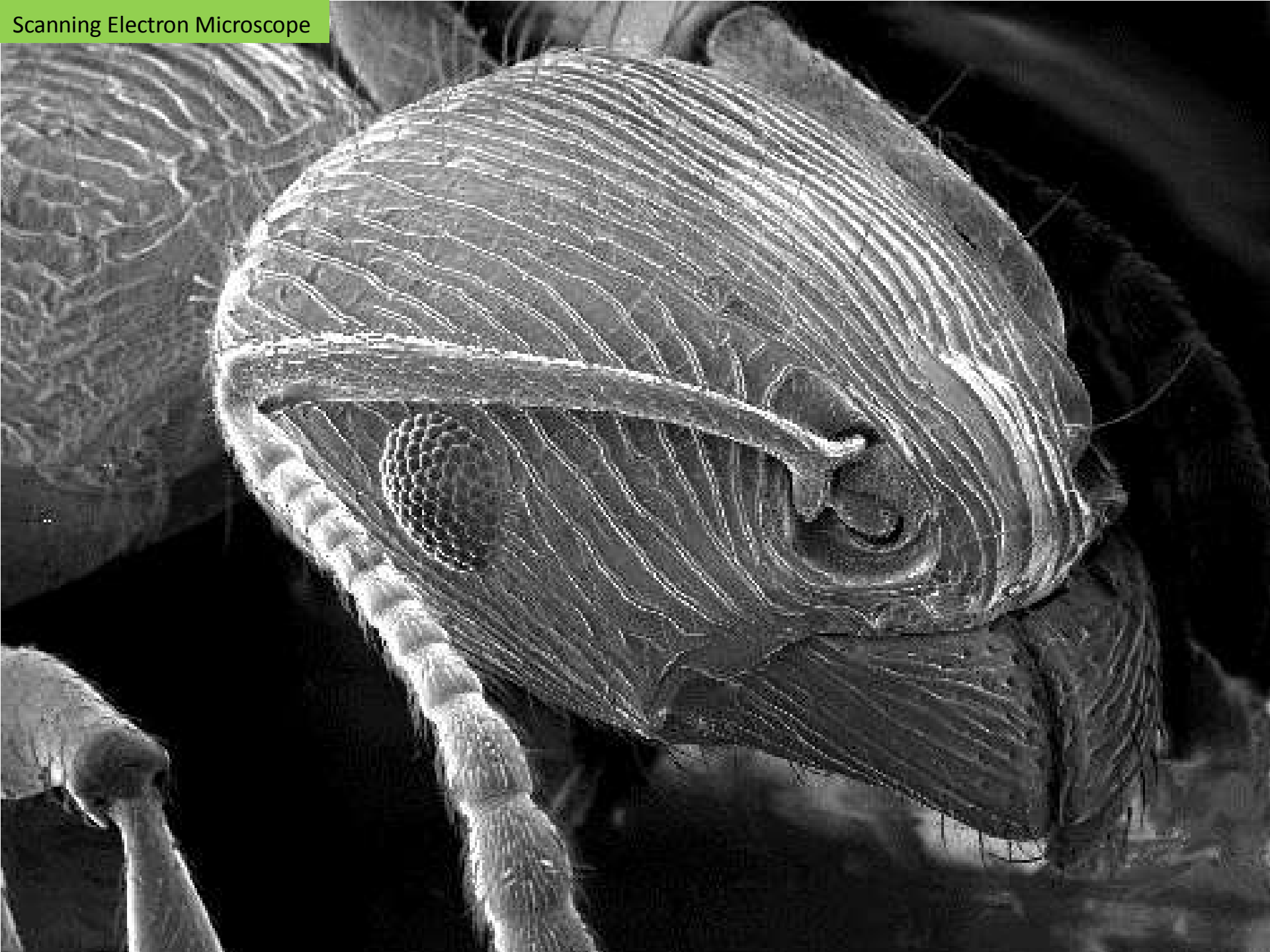




# From the Optical Microscope …

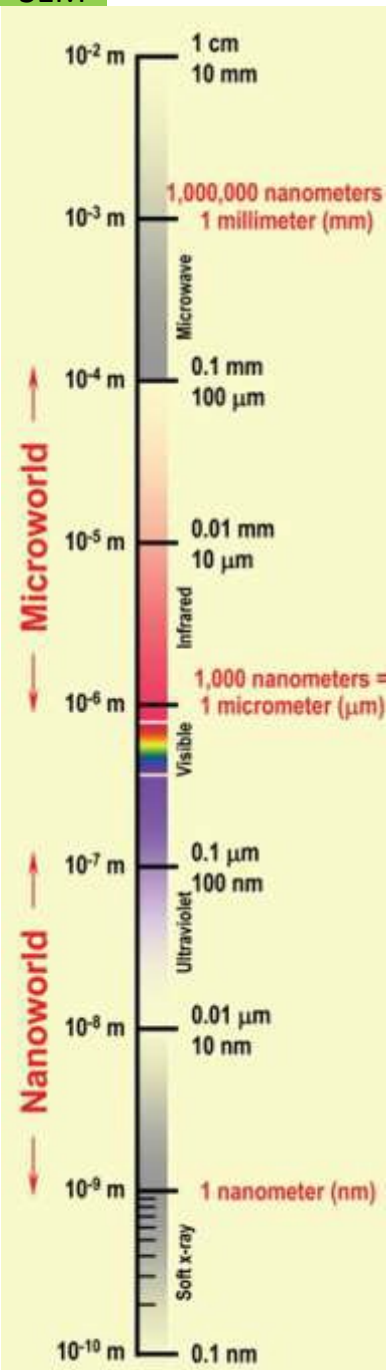
Ant
~ 5 mm

Scanning Electron Microscope



SEM


Lisa Del Muro @lisa_delmuro 28 Aug
got a WOW as soon as class moved the sample from the optical to SEM one student asked why image in black/white :)
pic.twitter.com/j1Q1EAXET8
Retweeted by shreya
Hide photo
Reply
Retweeted
Favorite
More
1
RETWEET
12:22 PM - 28 Aug 13 · Details
Flag media




# Scanning Electron Microscope

- What does it do?
  - Let's let Abby, from the TV Show NCIS, explain…
- How it works, on a high level.
- Where it's used.
- What subjects can be taught with it.
- What skills your students can learn from it. *(this is subjective)*

# NCIS' "Abby" – explaining the SEM

http://www.youtube.com/watch?v=W4HnH6Ar6pw

SEM

## Five Microscopes
to fit the scale of things

3D Optical
3D Optical Profiler

Scanning Electron (SEM)

Atomic Force (AFM)

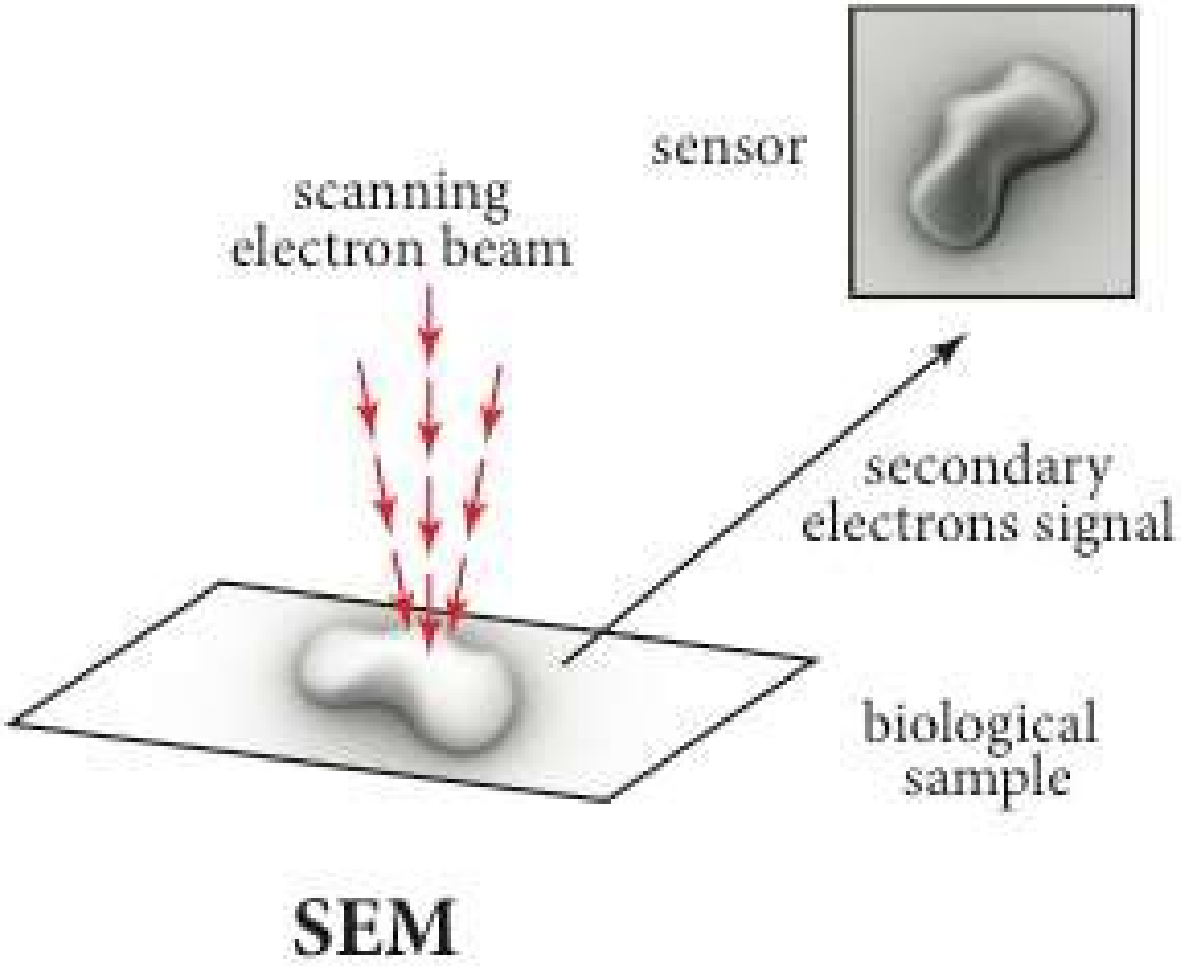
Transmission Electron (TEM)

Scanning Tunneling (STM)

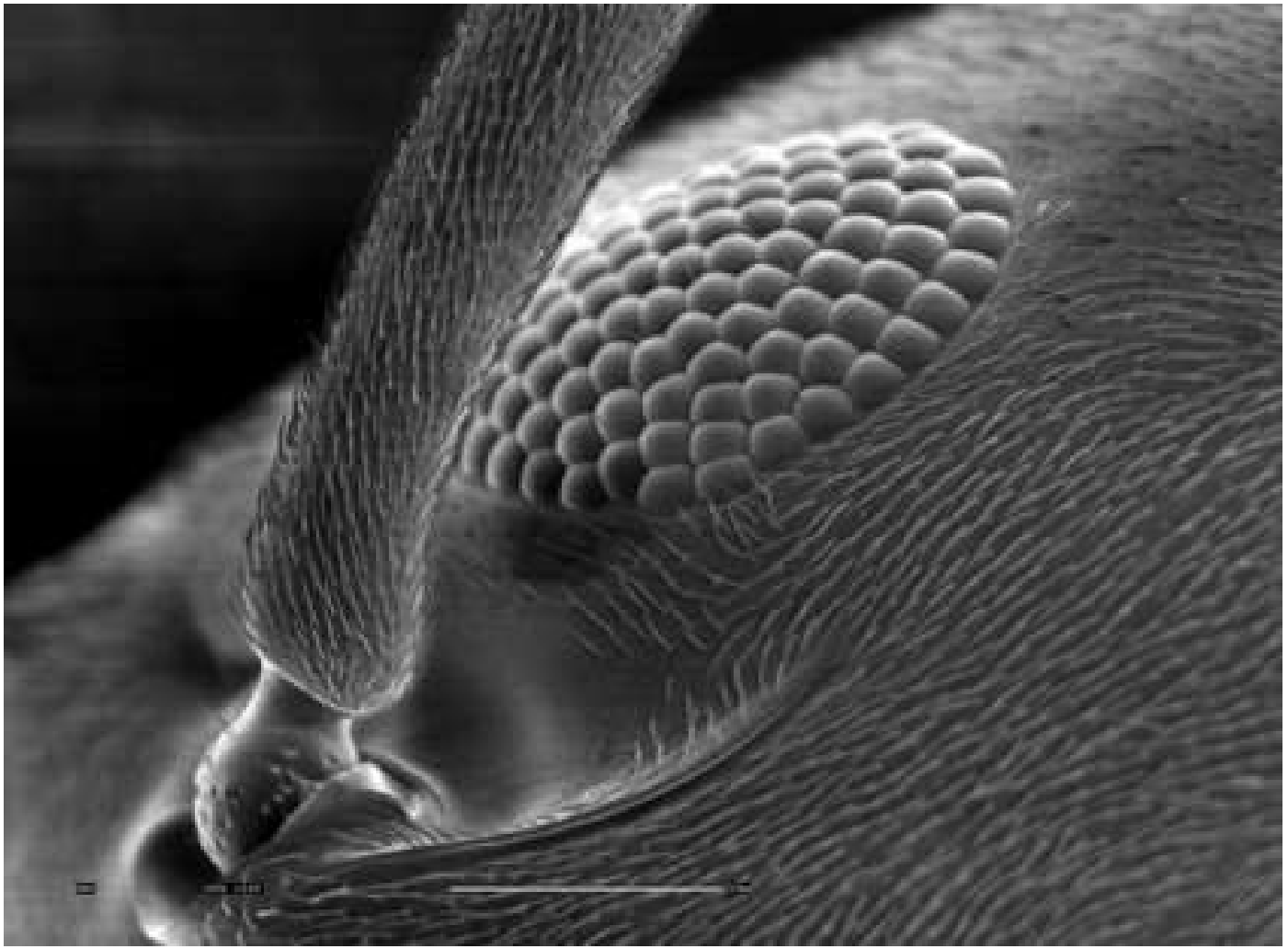
# Scanning Electron Microscope

- What it does.
- How it works, on a high level.
- Where is it used?
- What subjects can be taught with it.
- What skills your students can learn from it. *(this is subjective)*

# How it works


sensor
scanning
electron beam
secondary
electrons signal
biological
sample
SEM

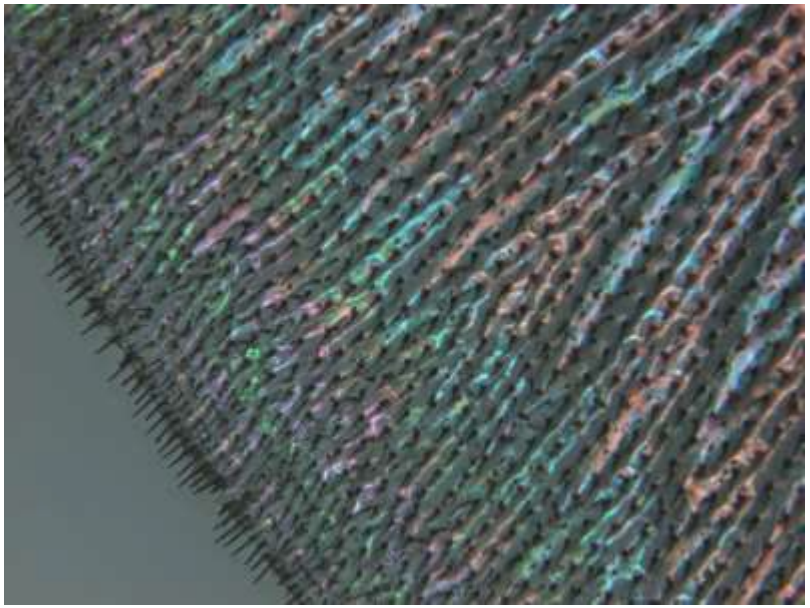
# Why is it black and white?




Color on the Optical Microscope

…

Hmmmm…

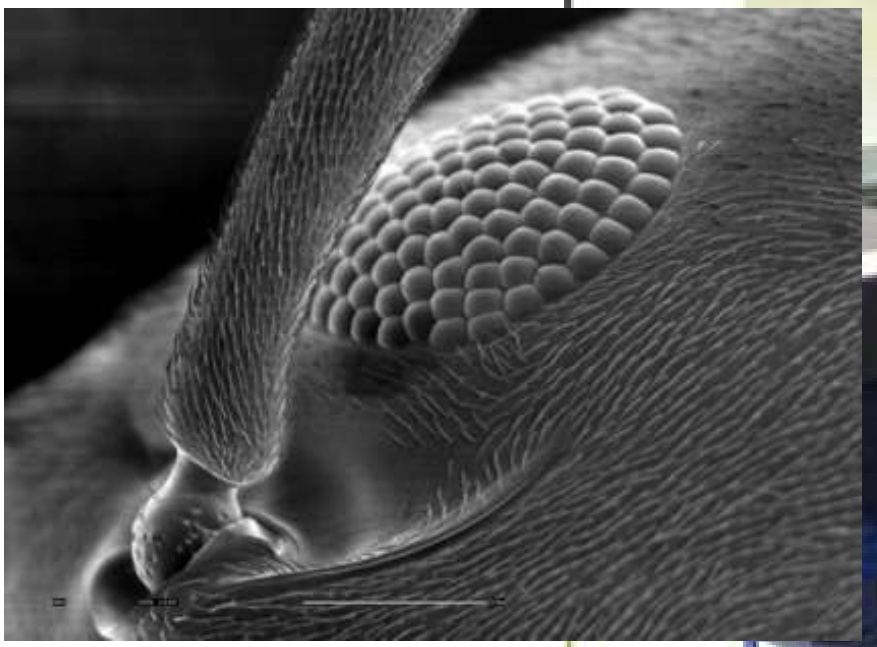


Fly Wing - Edge

Fly Back

Scanning Electron Microscope

No color on the electron microscope?

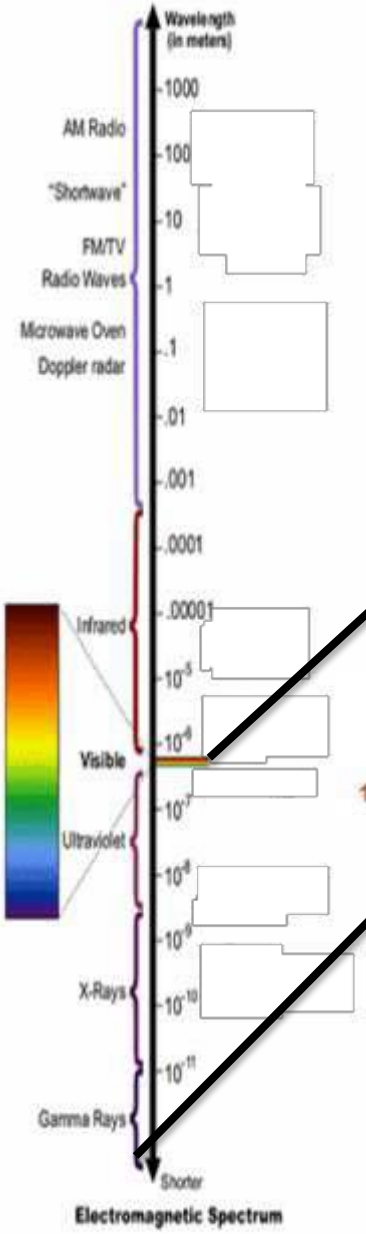


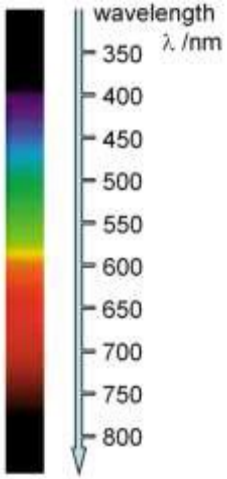
How does color work again?

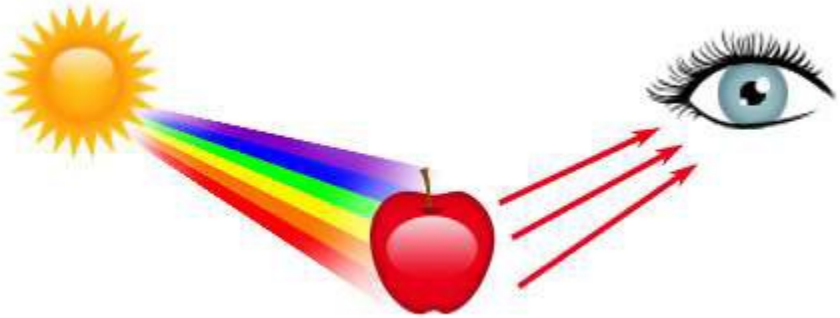
# Why Does an Apple Look Red?

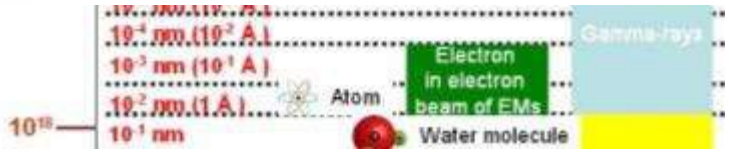

Title your paper, and record each of your observations.

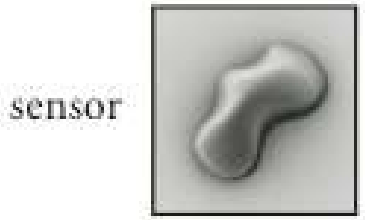
# SEM – How it works, described visually

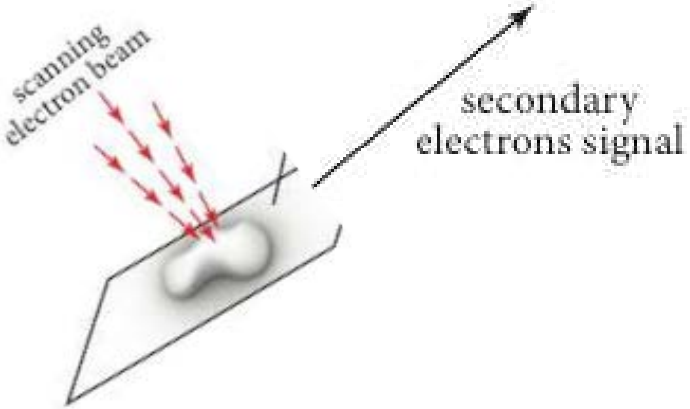




Well, technically...

In EMs, the kinetic energy (eV) gained by an electron as it is accelerated in the electron gun is equal to the electron's drop in potential energy ($V_0$). Therefore, we have,

$eV_0 = m_0v^2/2$ ---------- [4787a]

where,

v -- The electron velocity,

$m_0$ -- The electron rest mass.

Based on Newtonian theory, the relation between the wavelength ($\lambda$) of a particle (e.g. electron here), moving at a velocity, v, is given by the de Broglie wave equation:

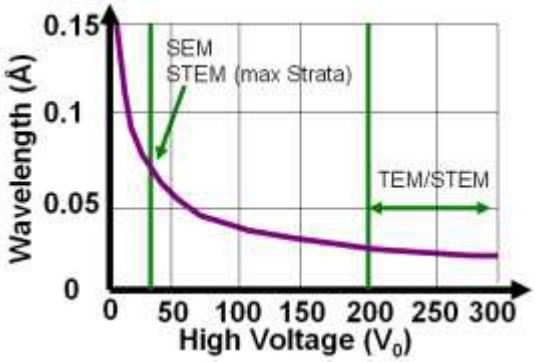
$\lambda = h/m_0v$ ---------- [4787b.a]

$= h/(2m_0eV_0)^{1/2}$ ---------- [4787b.b]

where,

h -- The Planck's constant.

Because the accelerated electrons have a speed of approximately light speed (c), they should be treated using relativistic quantum mechanics, which are important in electron microscopy since the electrons are typically accelerated to potentials of 30 to 400 keV (about half the speed of light). By introducing the correction for relativistic effects, the wavelength is given by,

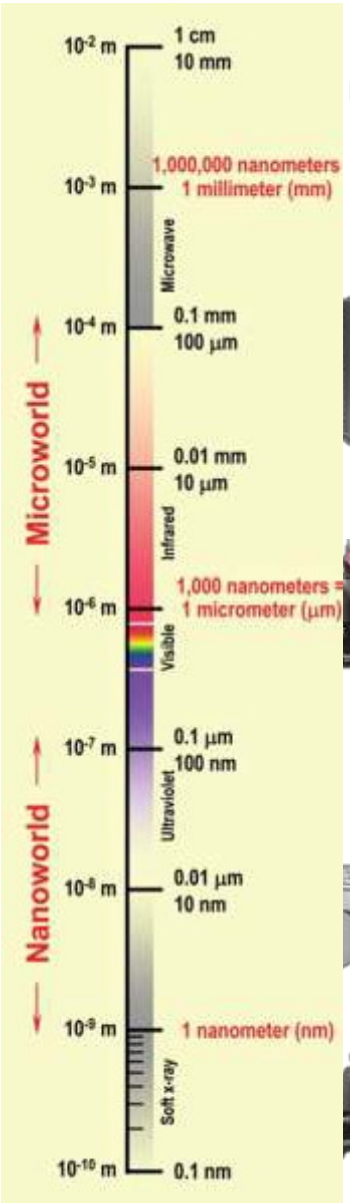



$$\lambda = h/\left[2m_0eV_0\left(1+eV_0/2m_0c^2\right)\right]^{1/2}$$

The wavelength of the electrons is dramatically decreased with increase of the acceleration voltage; therefore, the spatial resolution of the microscopes is significantly improved. Note that, in electron microscopy it is normally sufficient only to replace the mass and wavelength of the electrons with the corresponding relativistic values [1]. Therefore, the relation between $\lambda$ and $V_0$ can be given by,

$$\lambda = \frac{1.23}{\sqrt{V_0+10^{-6}V_0^2}}\,nm$$

# Five Microscopes
to fit the scale of things




**3D Optical**

3D Optical Profiler

**Scanning Electron (SEM)**

**Atomic Force (AFM)**

**Transmission Electron (TEM)**

**Scanning Tunneling (STM)**

# Scanning Electron Microscope

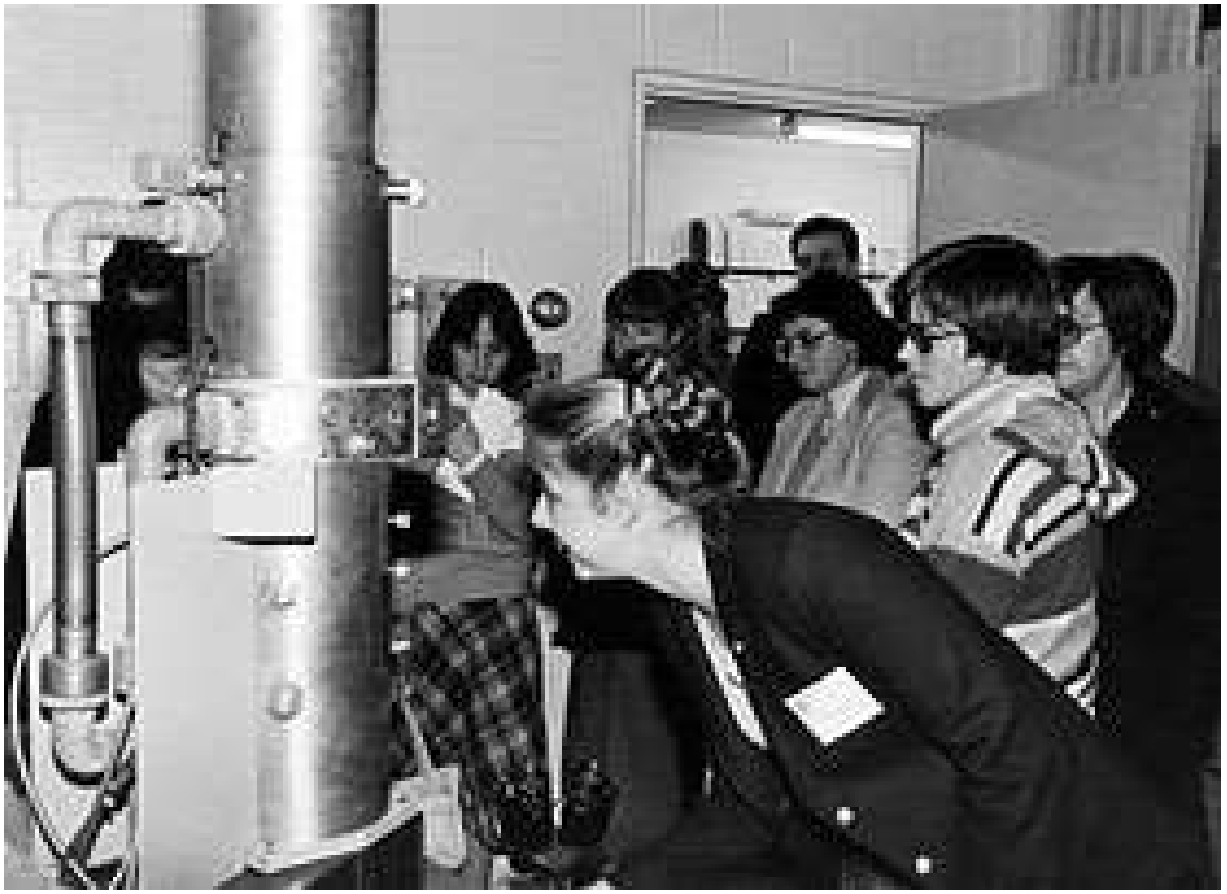
- What it does.
- How it works, on a high level.
- **Where is it used?**
  - Scanning Electron Microscopy is used in virtually every high technology and scientific area.
  - Additionally, there is a strong focus on including SEM in forensic analysis, as depicted here…
- What subjects can be taught with it.
- What skills your students can learn from it. *(this is subjective)*

# CSI NY

http://www.youtube.com/watch?v=dWe65XWsqHY

# SEM in Education

**Then….**



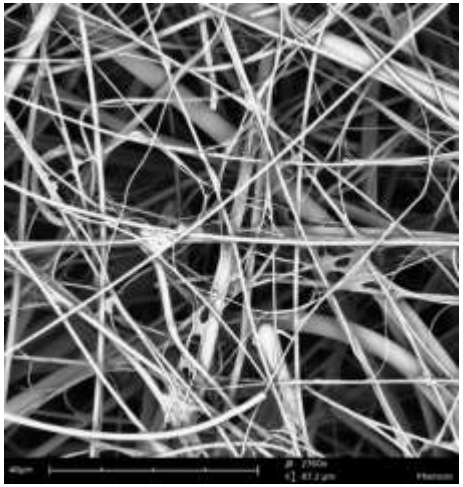
**…. And Now…**

## Phenom SEM and Students

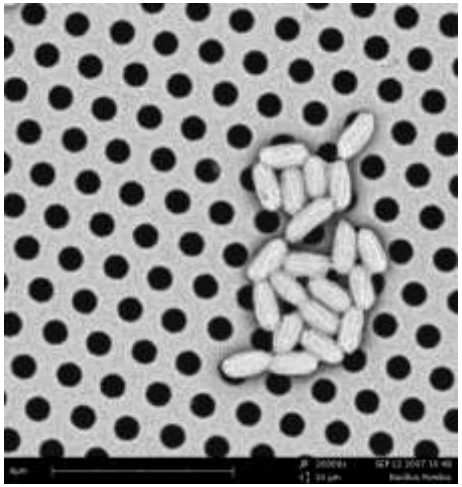

http://www.youtube.com/watch?v=OyrVL-Dy5RY

# Where SEM is used in industry:

**Aerospace:** nickel-base supper alloy

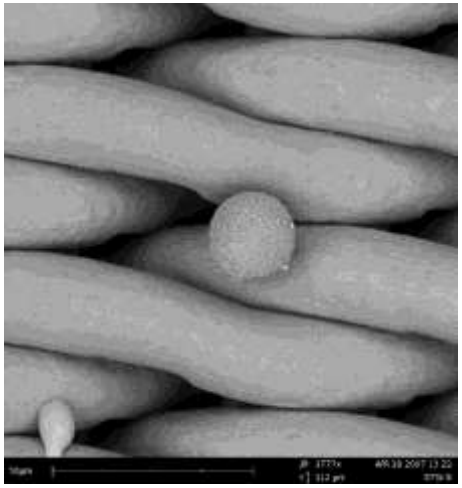


**Consumer Goods:** hepa filter

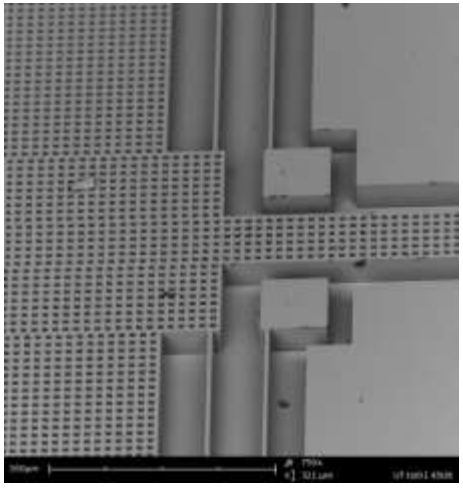


**Medical:** bacteria

**Pharmaceutical:** powder compound



**Industrial:** metal filter



**Semiconductor:** micro structure (MEMS)

# Also, colorized SEM images can be used as art:

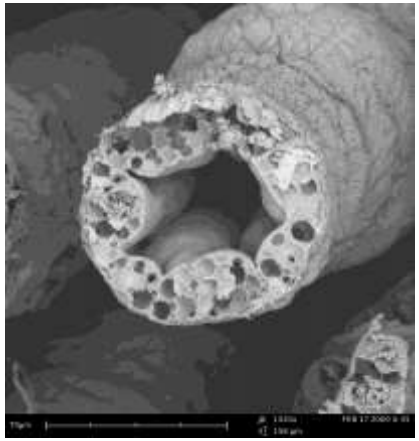
Fly mouth

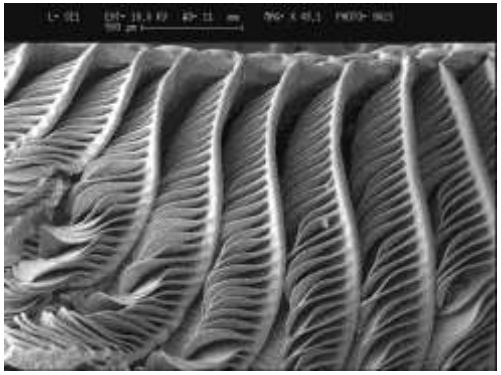
Penny

Green Mold

# Used in teaching, for example: Occidental College

*"We love the (SEM)." –Dr. Gary Martin, Biology Professor @ Occidental College*



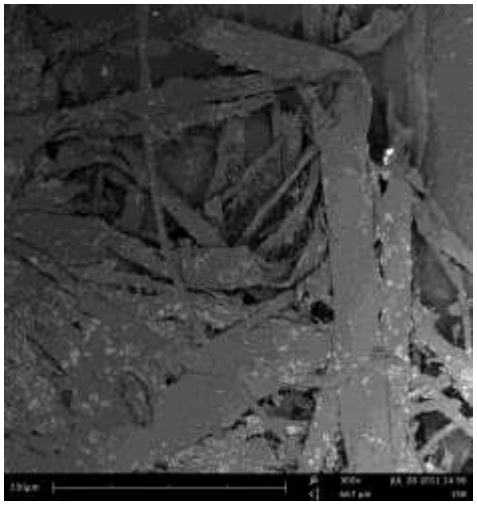


**Courses taught with the SEM:**
-Introductory Biology
-Upper division Invertebrate biology

**Other activities:**
-Student research
-Book chapters
-Publications

# Another example: Western New England University

***"This instrument enriches our program and helps students get interested and excited about science." –Dr. Robert Gettens, BioEngineering Professor @ WNE College***

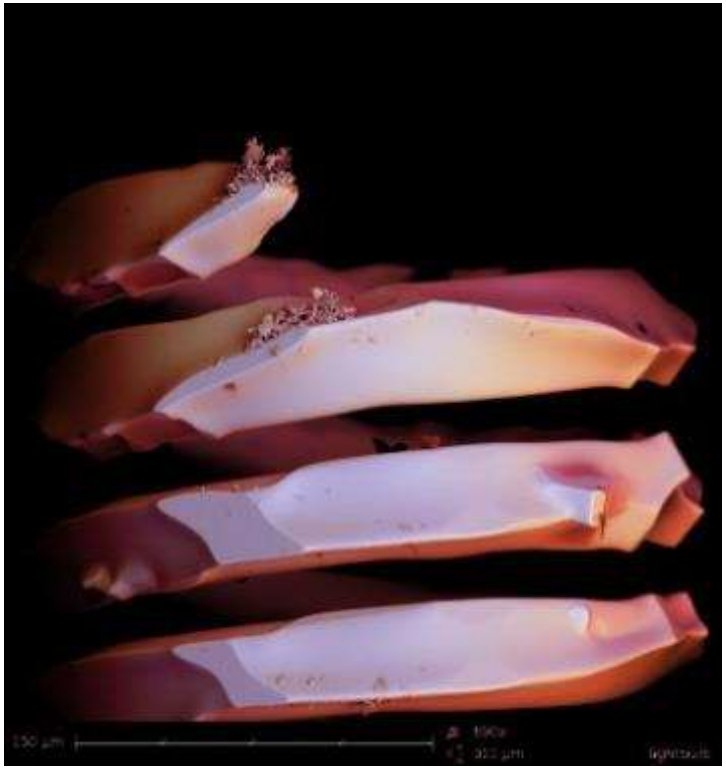


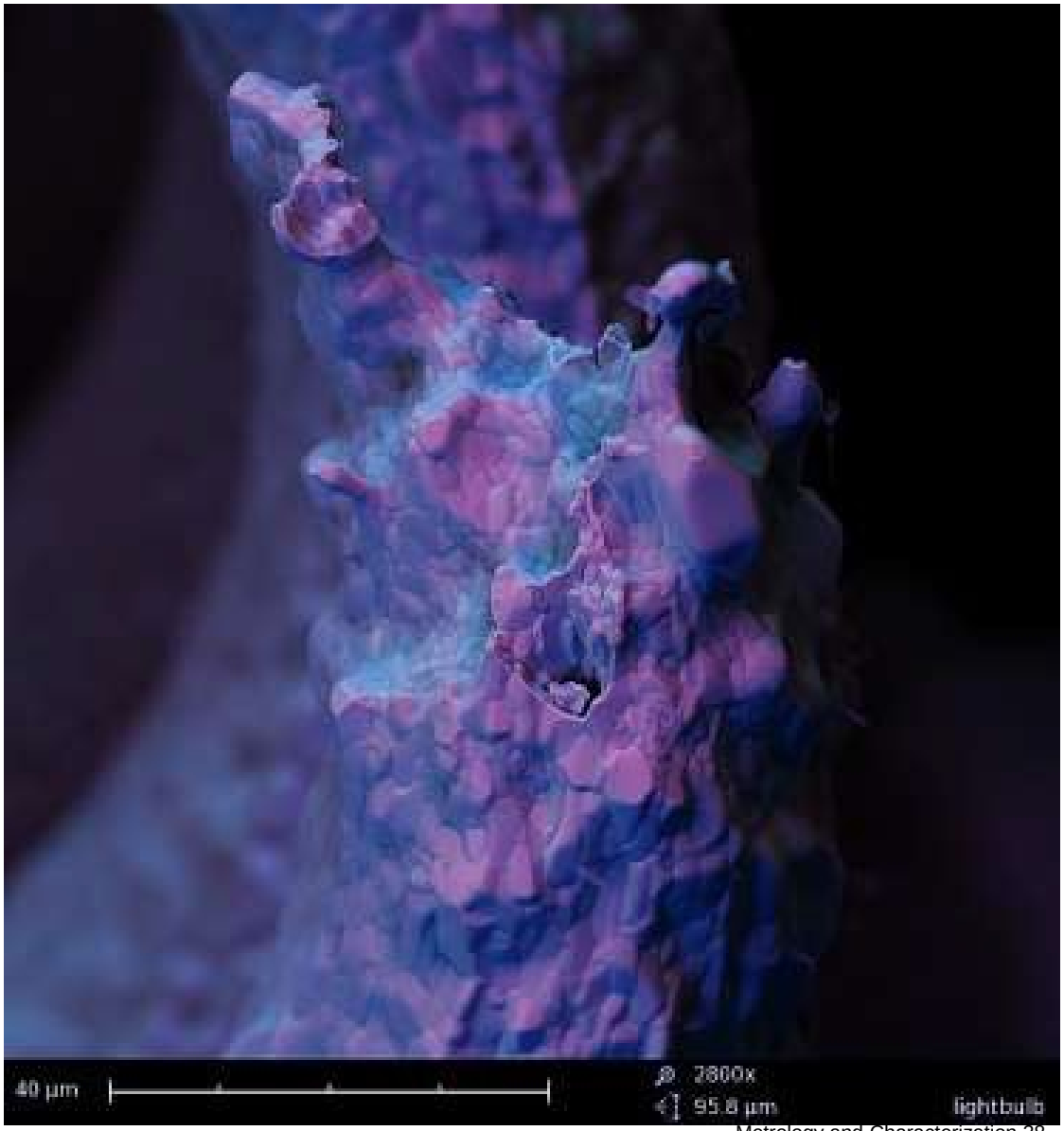
**Departments using the SEM:**
-Biomedical Engineering
-Chemistry

**Other activities:**
-Student research
-Industrial Collaborations
-Summer program for high school students

# And just cool stuff that you break:

**Colorized SEM images of a broken light bulb filament**

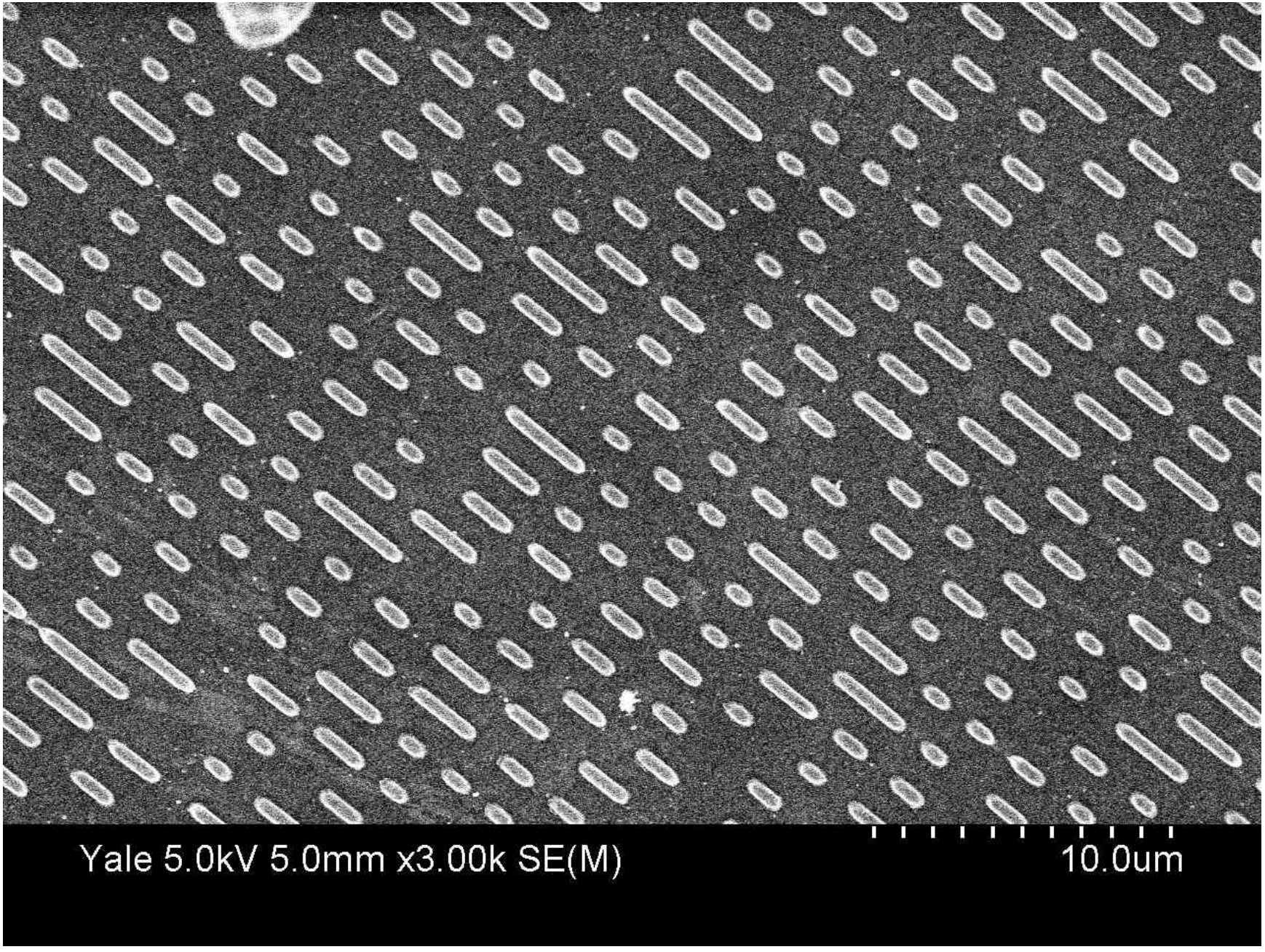




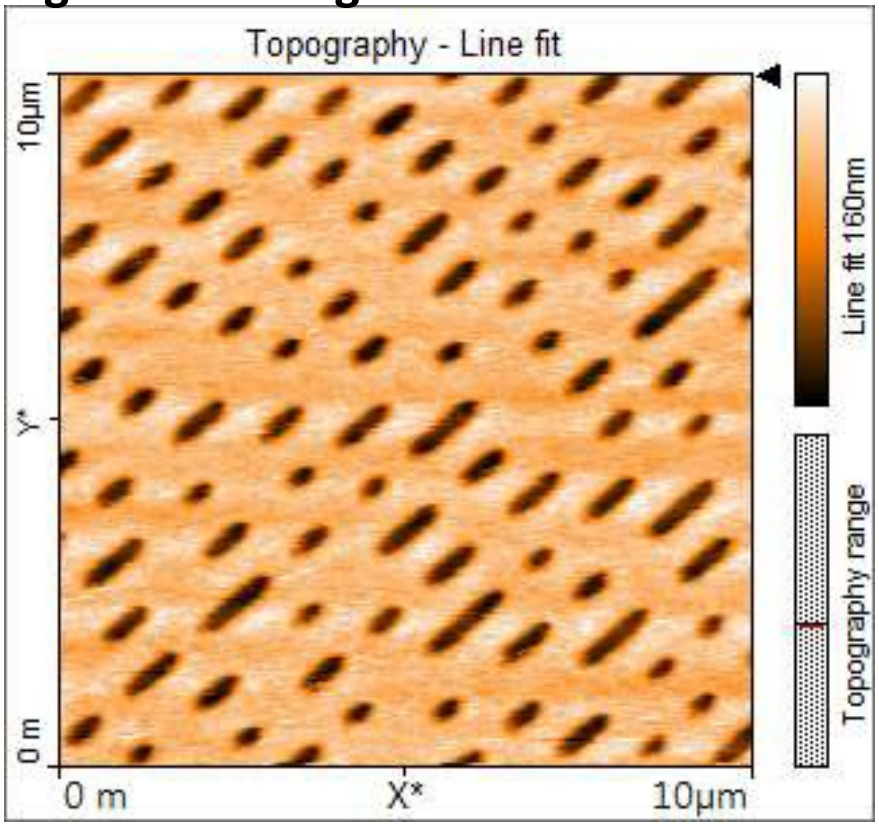
# Questions?

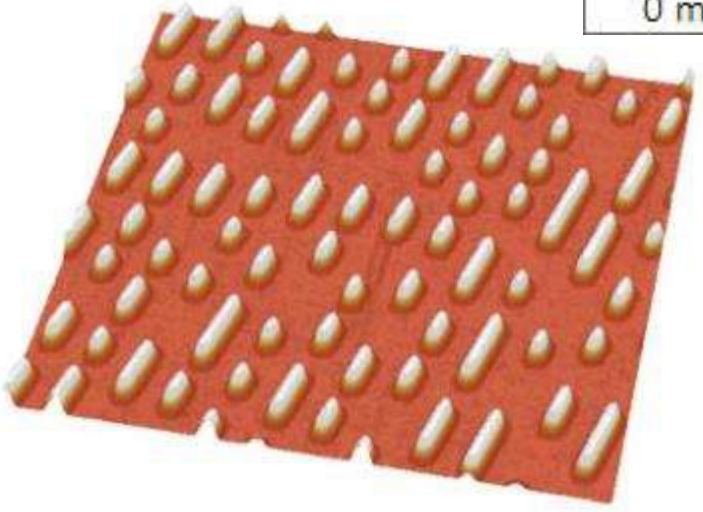
Please type all questions or comments into the Chat Box

**What do you think this is an SEM image of?**

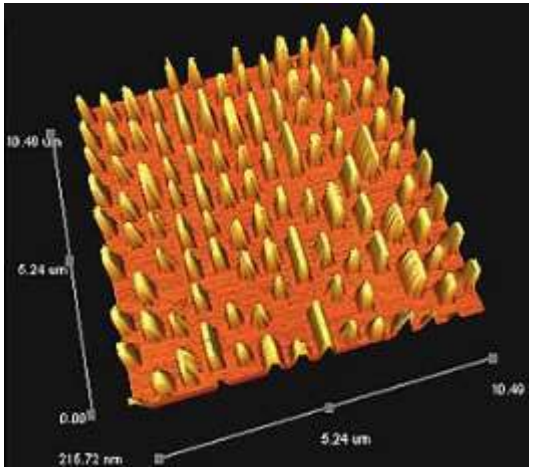


# Maybe it's easier to figure out using an Atomic Force Microscope?

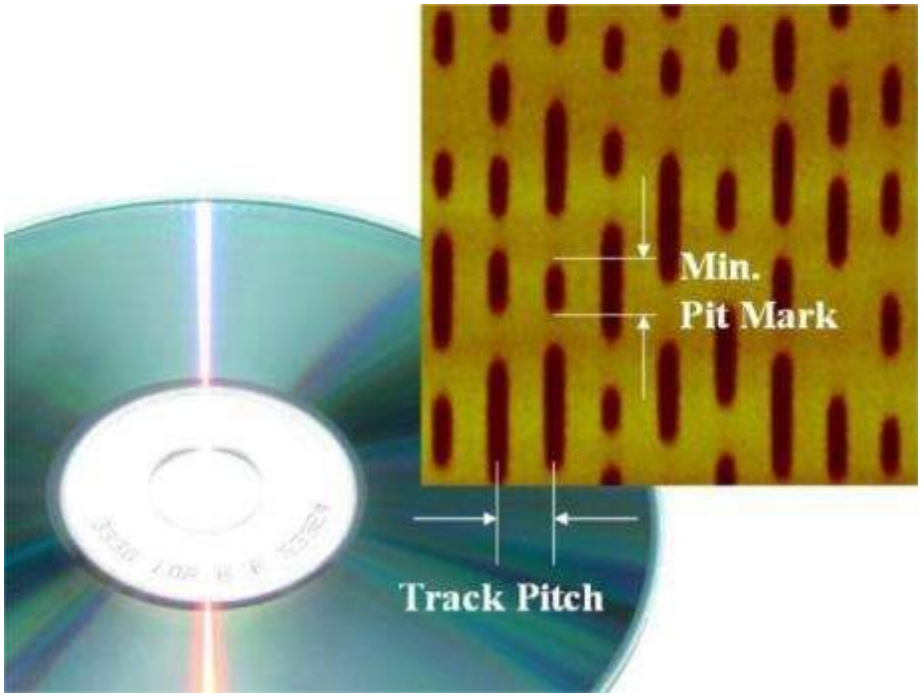


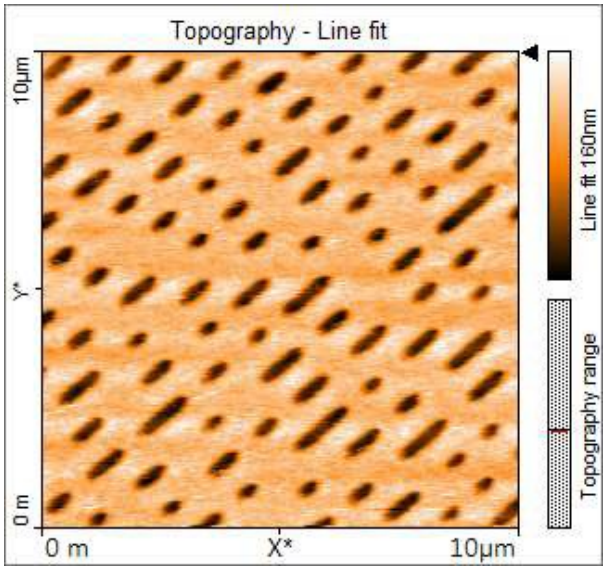



***Still no idea?***

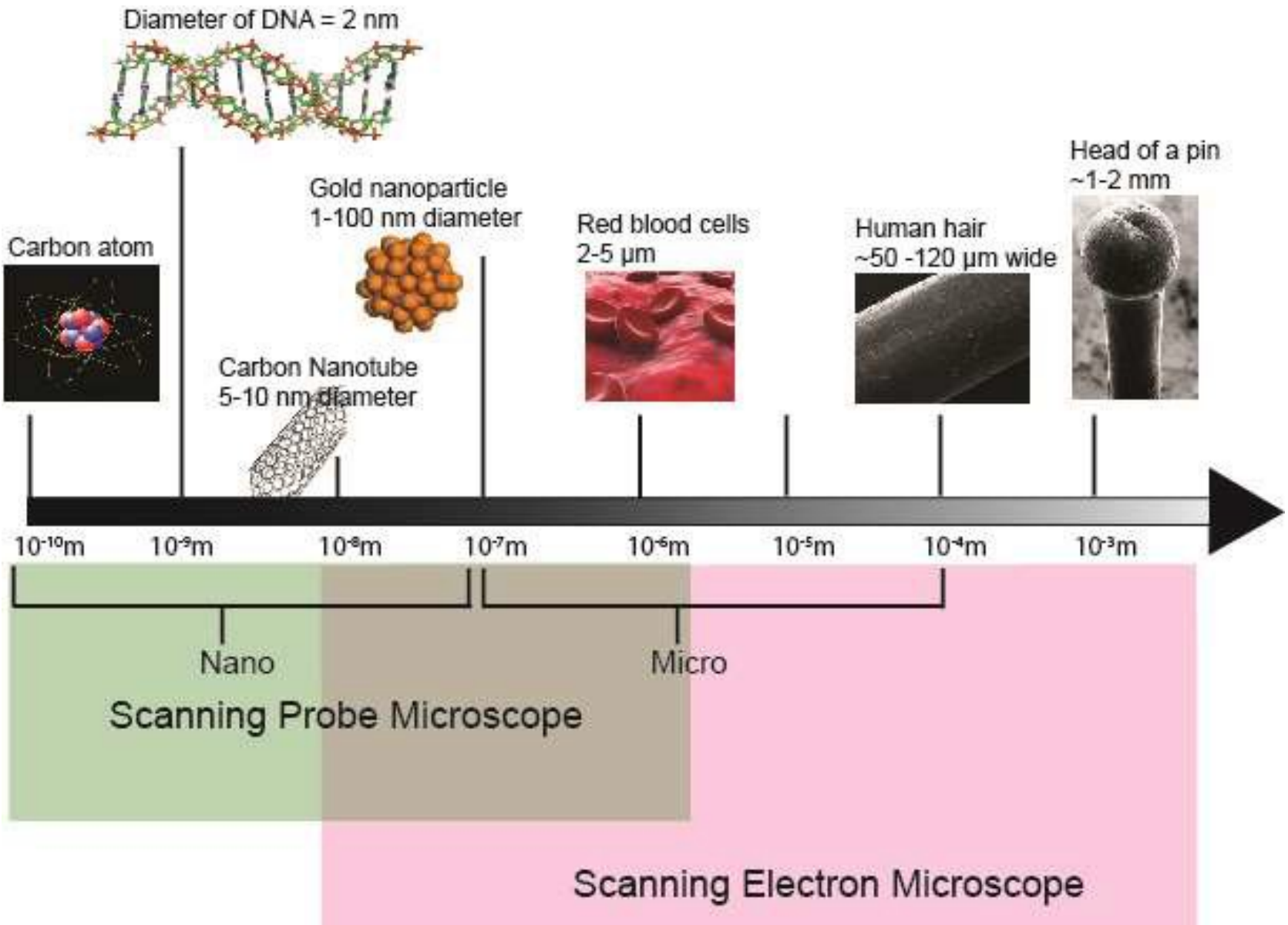


# A DVD!

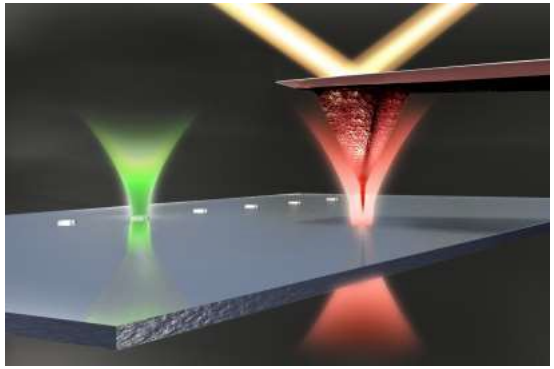

Min.
Pit Mark
Track Pitch

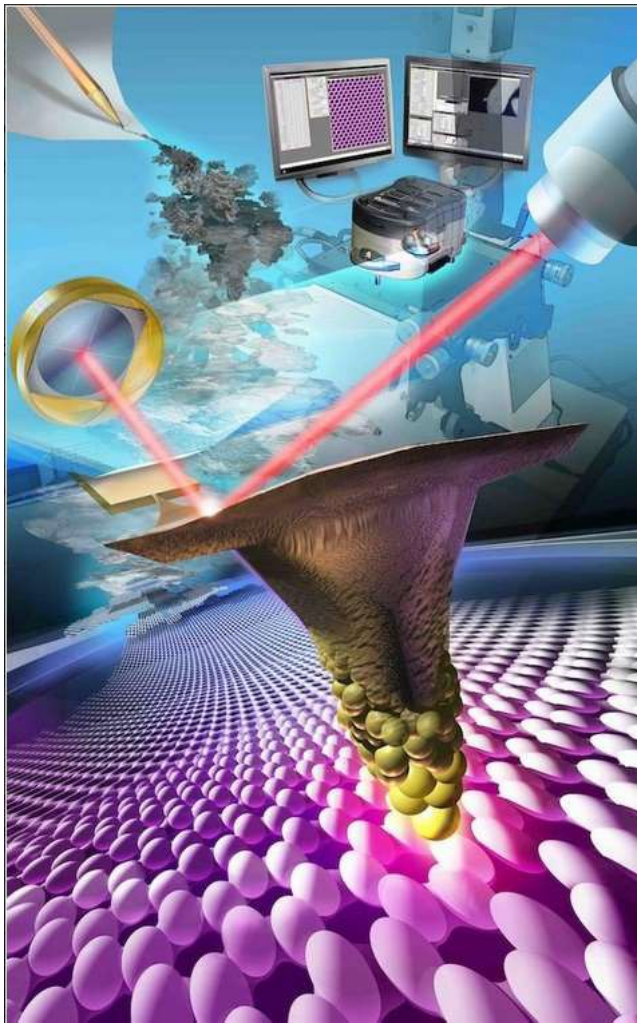

Topography - Line fit
10µm
Y*
0 m
0 m
X*
10µm
Line fit 160nm
Topography range

# Is AFM essential to “nano”?

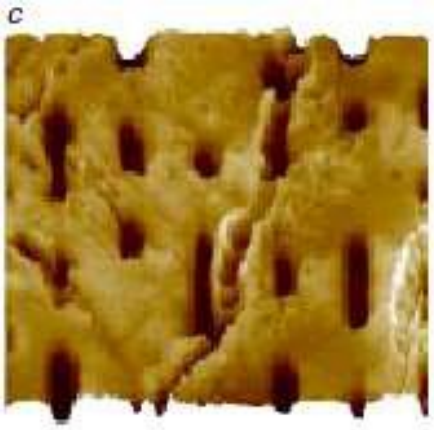


# AFM – The Poster Child of Nano …





# Why won't my CD play after my 2-year old has slid it across the floor?

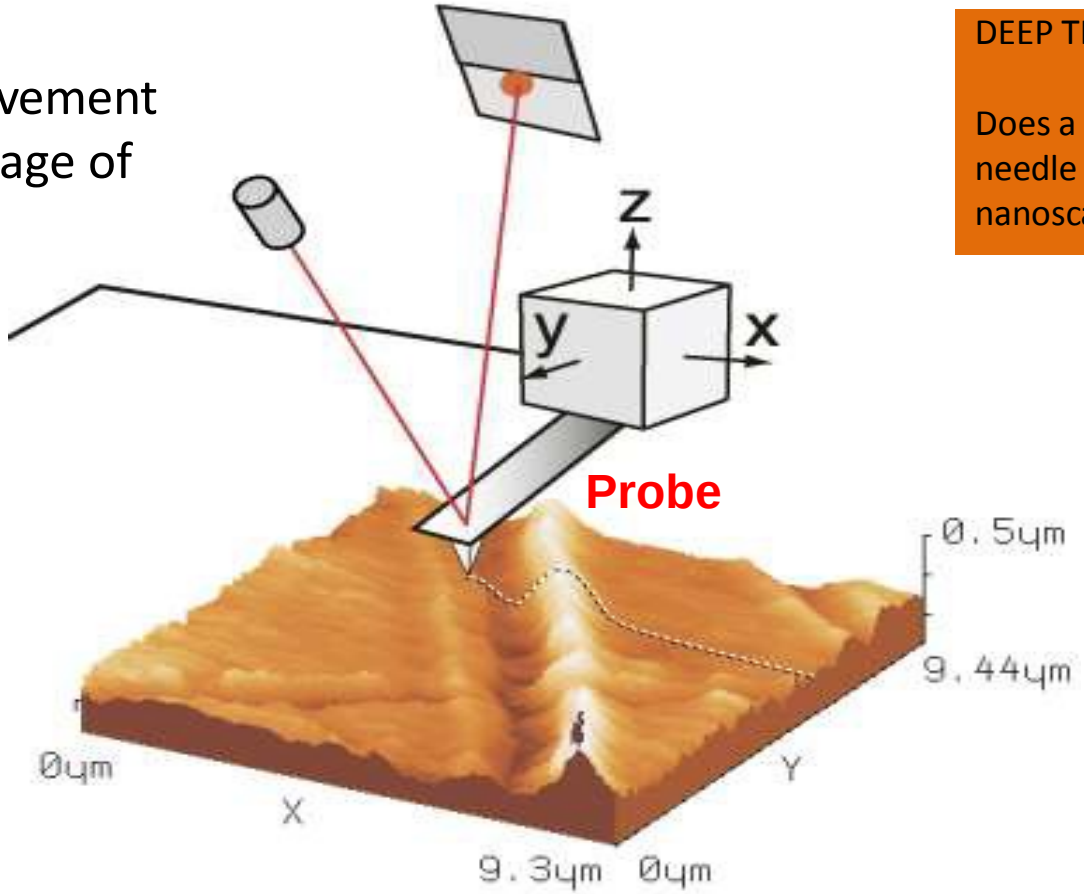



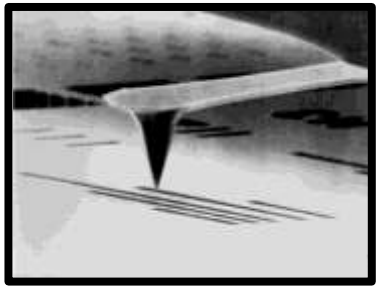
In simple terms, the atomic force microscope works by scanning a sharp probe over the surface of a sample in a raster pattern.

By monitoring the movement of the probe, a 3-D image of the surface can be constructed.

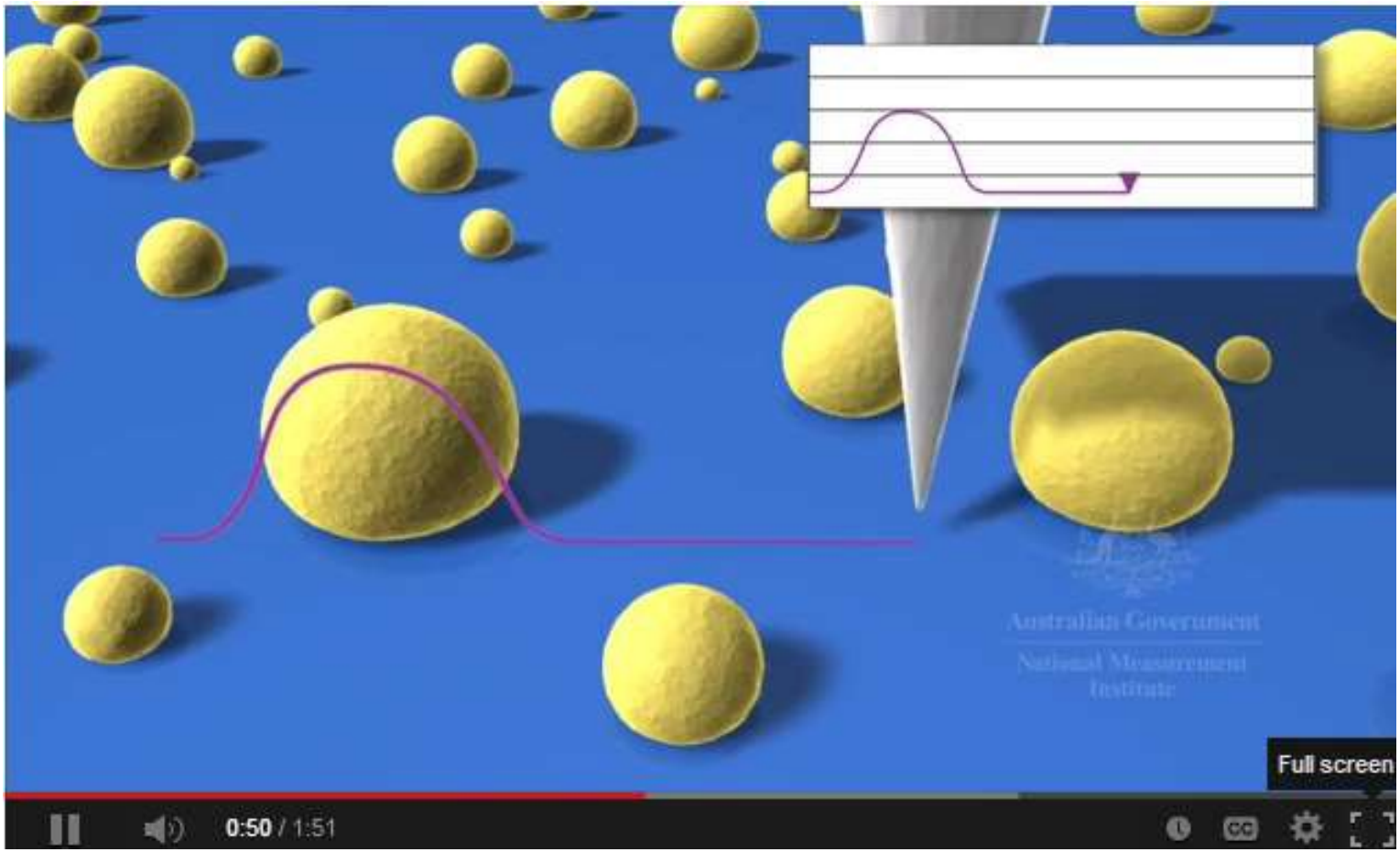
DEEP THOUGHT…

Does a record player needle touch at the nanoscale?



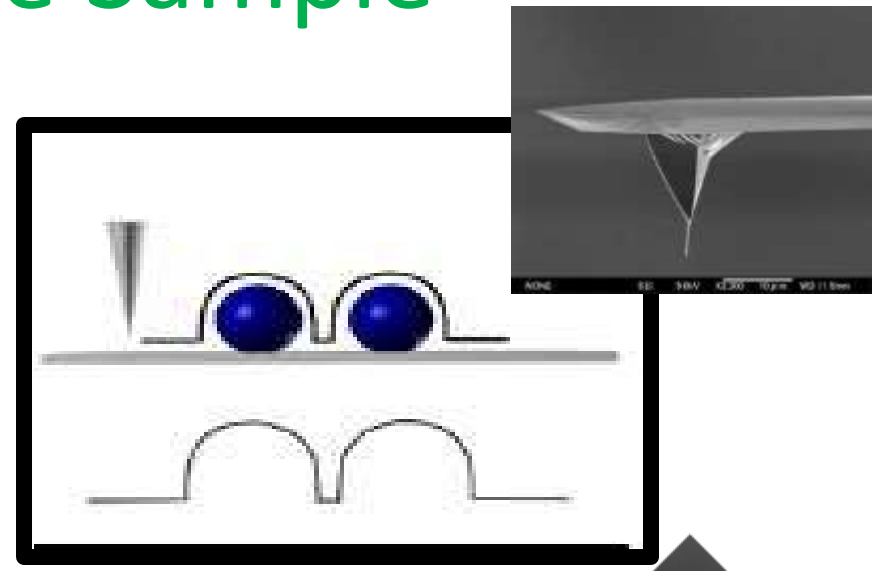
Abe Michelen, PhD
Director, NEATEC T: 518.698.9312

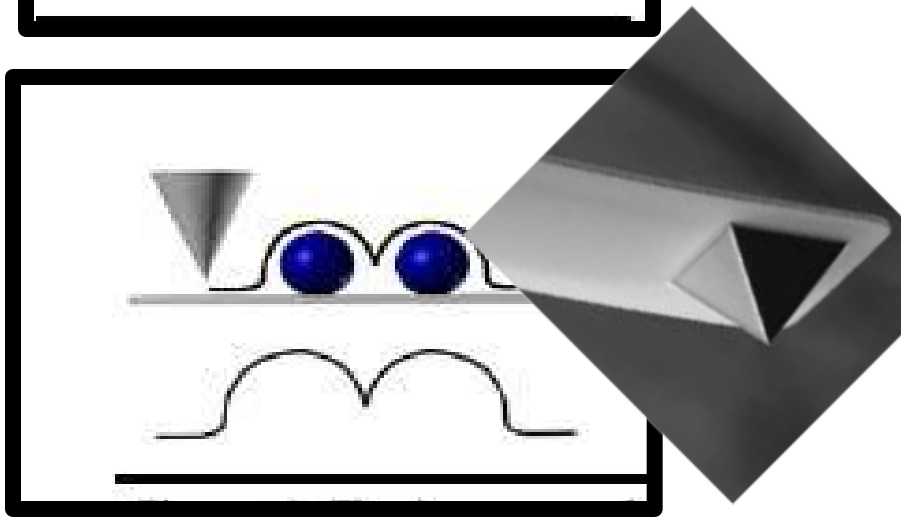



http://www.youtube.com/watch?v=Ha53tFTsmW8

# Scanning the Sample

- Tip brought within nanometers of the sample (van der Waals)
- Radius of tip limits the accuracy of analysis/ resolution
- Stiffer cantilevers protect against sample damage because they deflect less in response to a small force





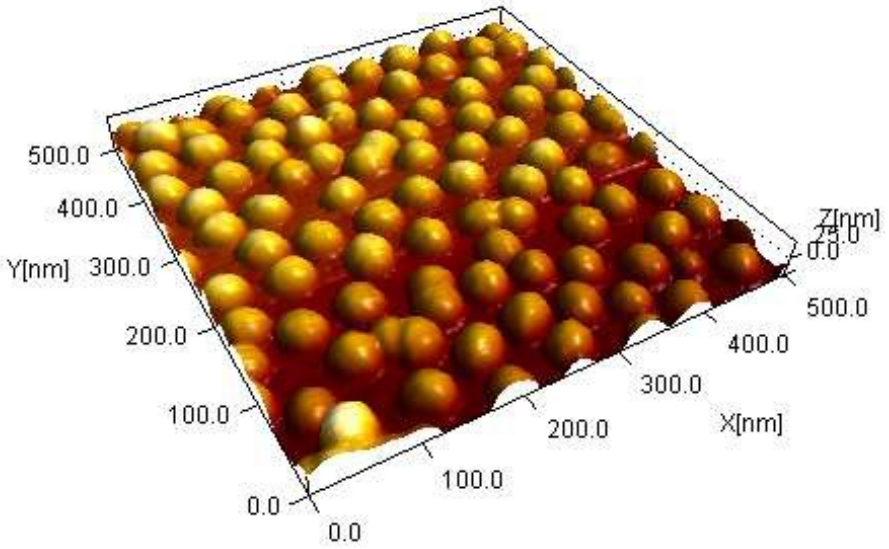
# Particle Analysis

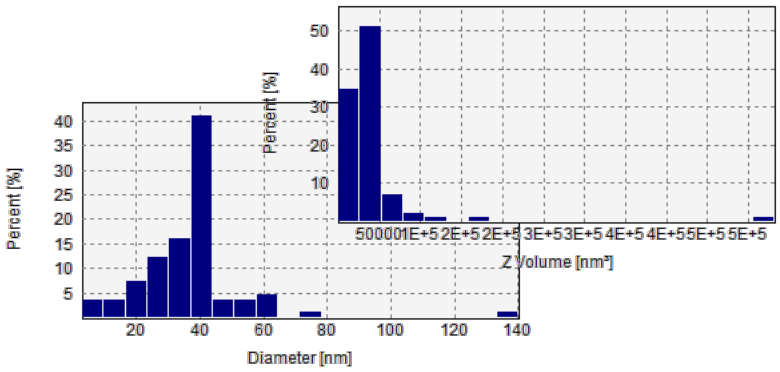
AFM can easily discern nanometer size particles/additives

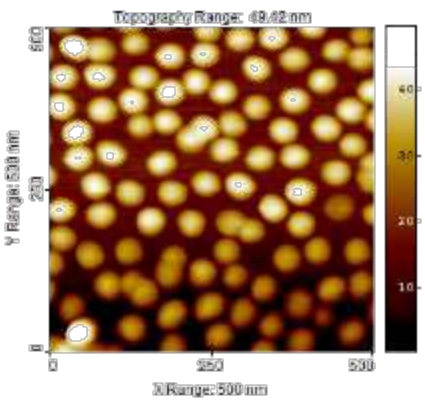
**Consumer Goods:** Cosmetics, Hair Care, Paints/Dyes

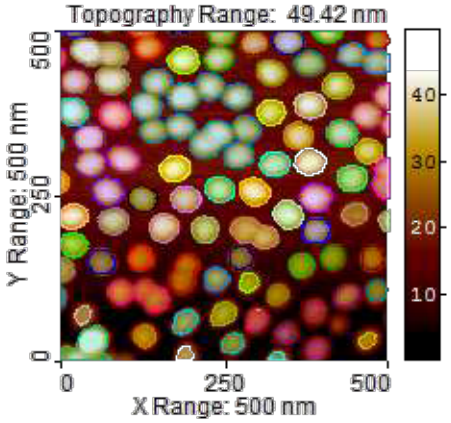
**Medical:** Drug Delivery, Pill fillers, Active ingredients

**Industrial:** Structural additives



# Nanotubes

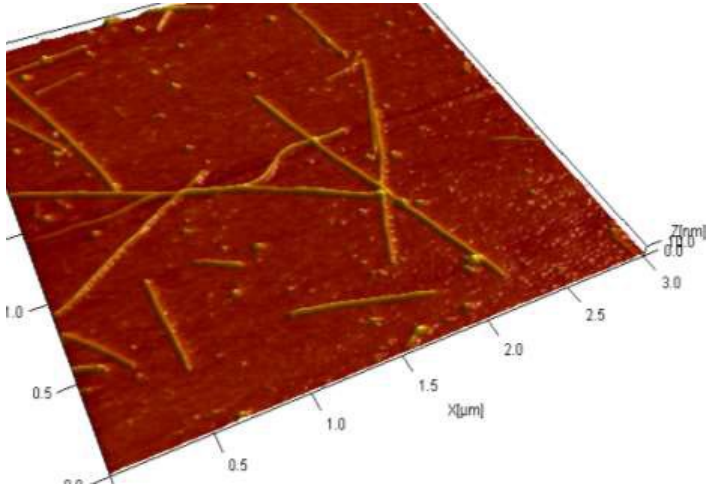
AFM is the technique of choice for characterizing carbon and other nanotubes. Length, diameter, and density can easily be determined.

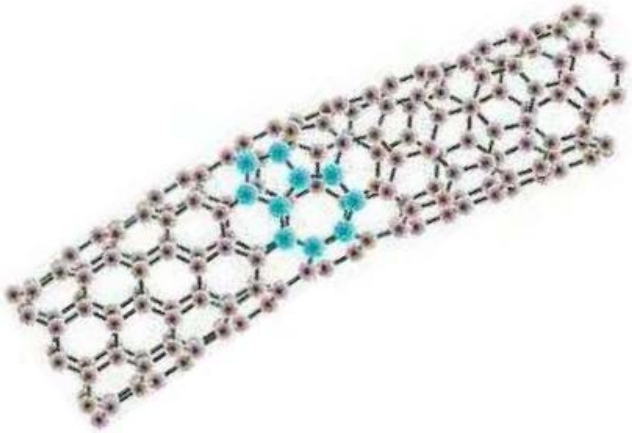
**Structural:** Windmills, Car frames

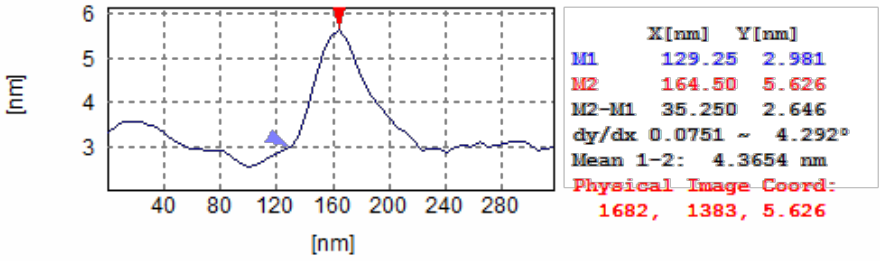
**Biological:** Pathogen detection, Bone scaffolding

**Energy:** Windmills, Solar cells

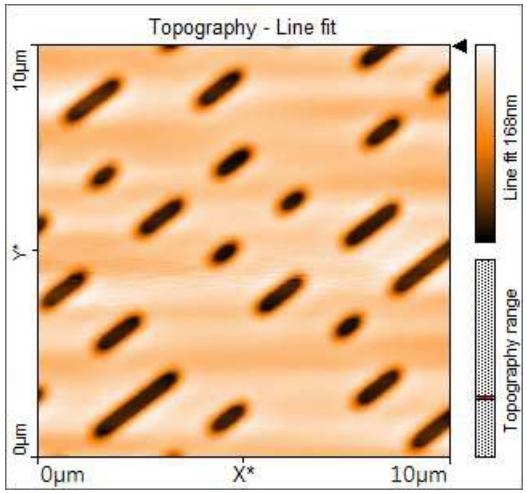
**Consumer:** Flexible electronics

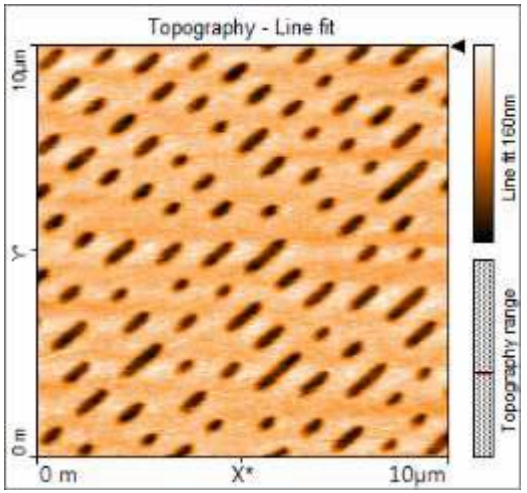


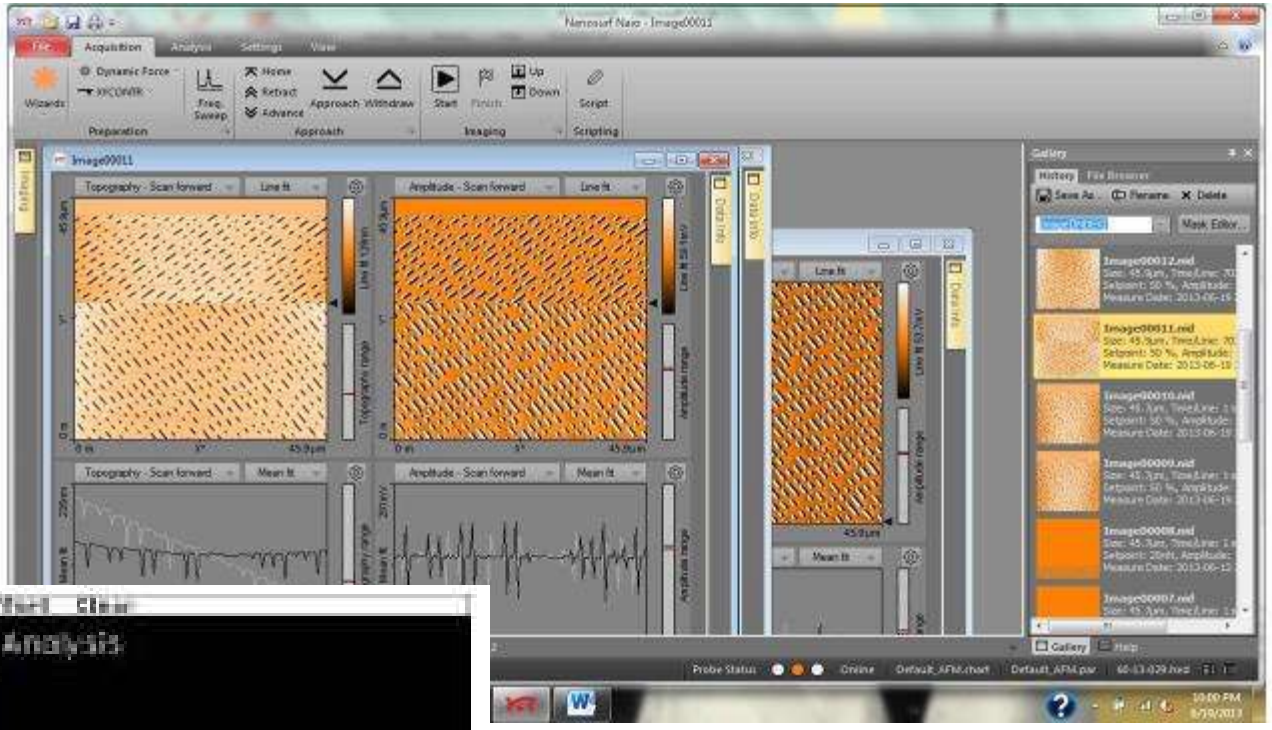


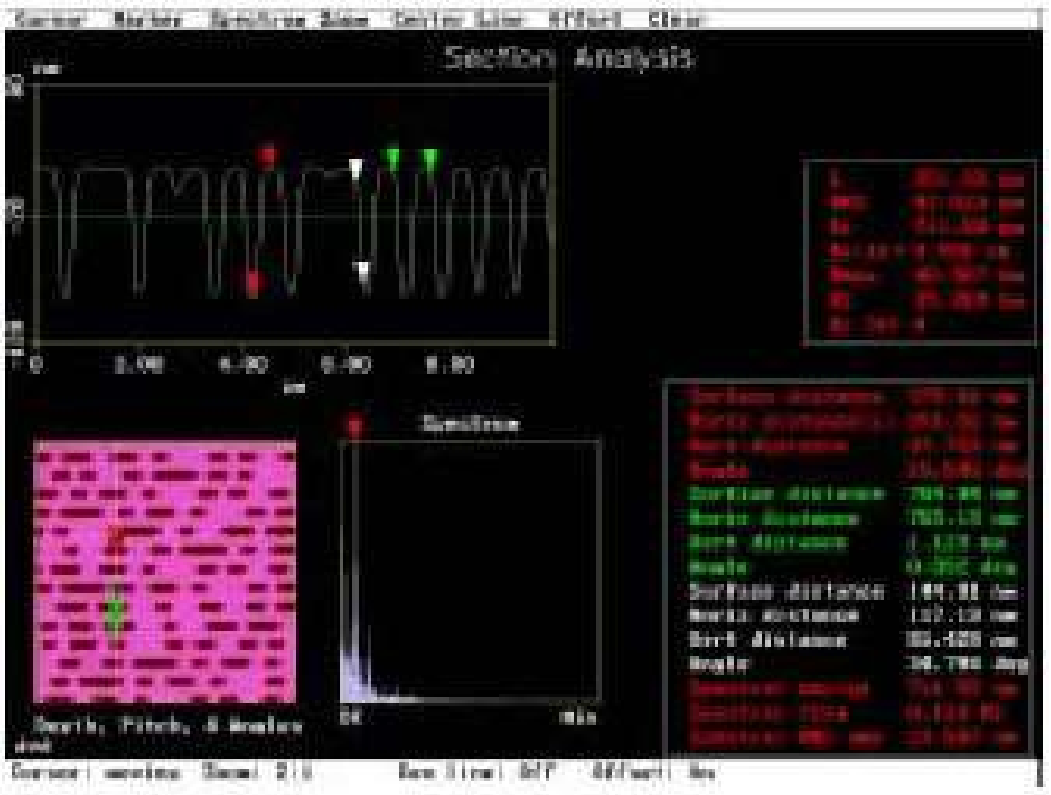
# Why are all the AFM images “orange”?

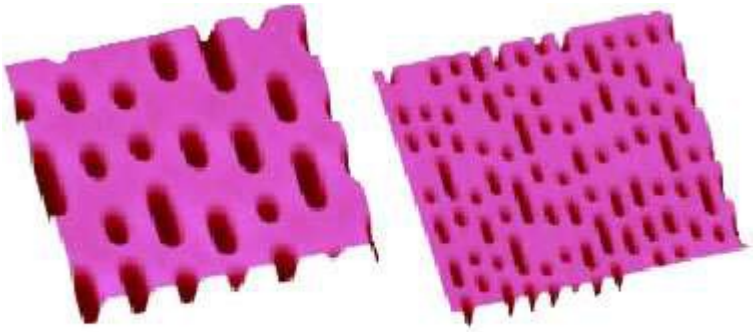


AFM





a b

*TappingMode AFM perspective images of a) CD disc and (b) DVD disc. 10μm scans.*

Speaking of Color…

A Matching Game…

Match the AFM image to the Disk



Mike Davis

Mike Davis

✓ Friends

Timeline About Photos 161 Friends 67 Mutual

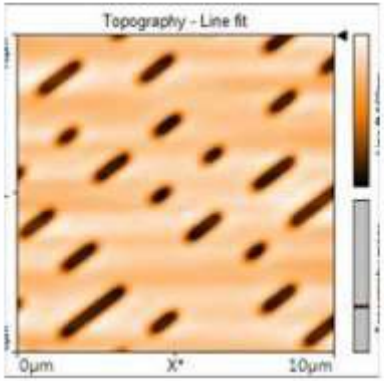
Photos

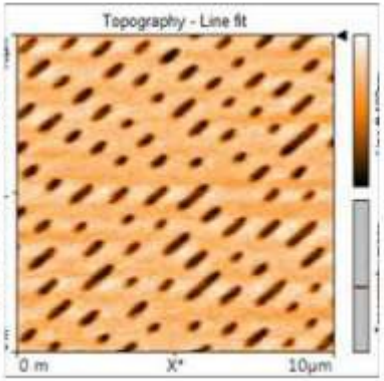
Photos of Mike Mike's Photos Albums

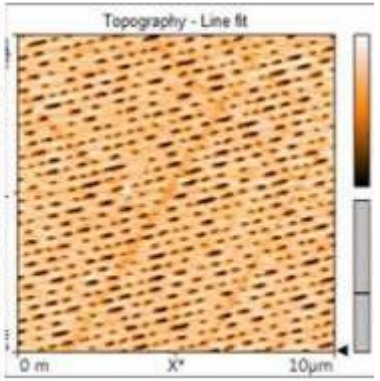
**AFM Images I took in my basement.**

Updated about a month ago

15 years ago, if you told me I would have an AFM in my basement, I would have been pissed as hell. "Can't I leave that damn thing at the lab!". Now I think its pretty awesome, and I would give almost anything for one of the hundreds of crappy samples I lost or threw away in grad school.



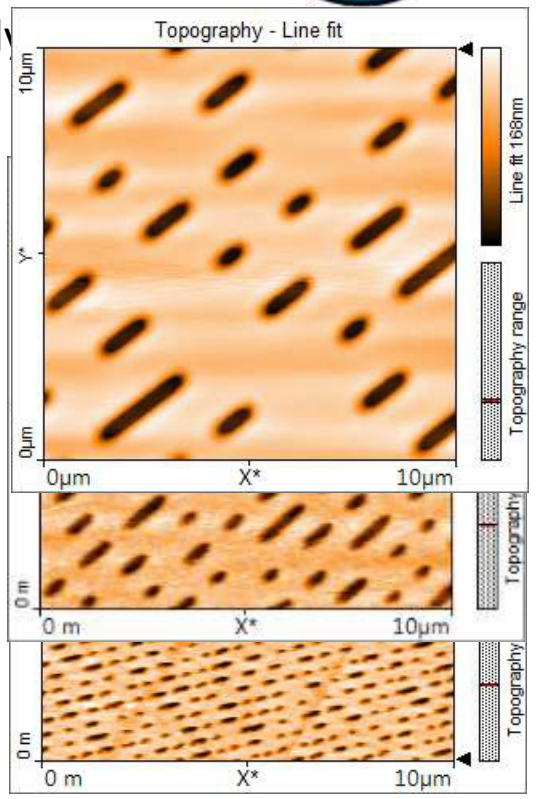



AFM



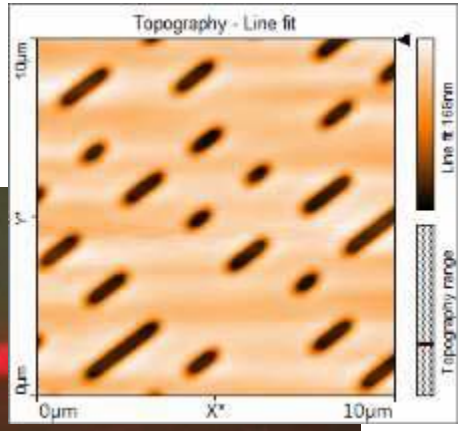

- ✓ CD..
- ✓ … DVD…
- ✓ … Blue Ray..
- ✓ A Blue Ray?
- ✓ Like a Ray Gun?
- ✓ Like a LASER Ray Gun?
- ✓ Like “*Light Amplification by Stimulated Emission of Radiation*”?

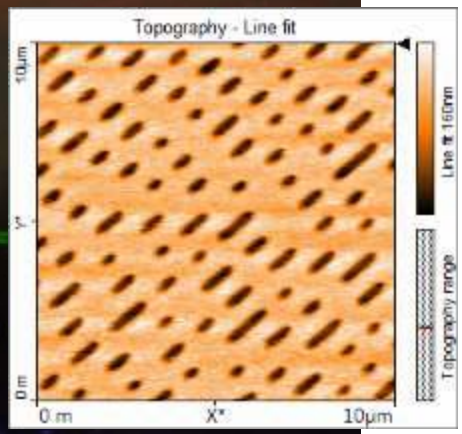



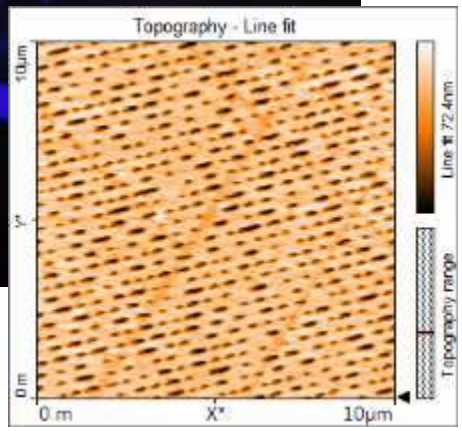

780 nm


650 nm

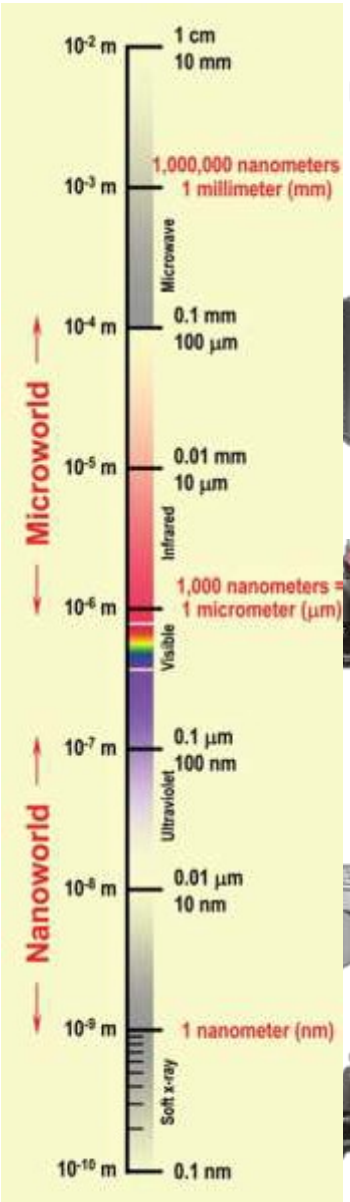

405 nm



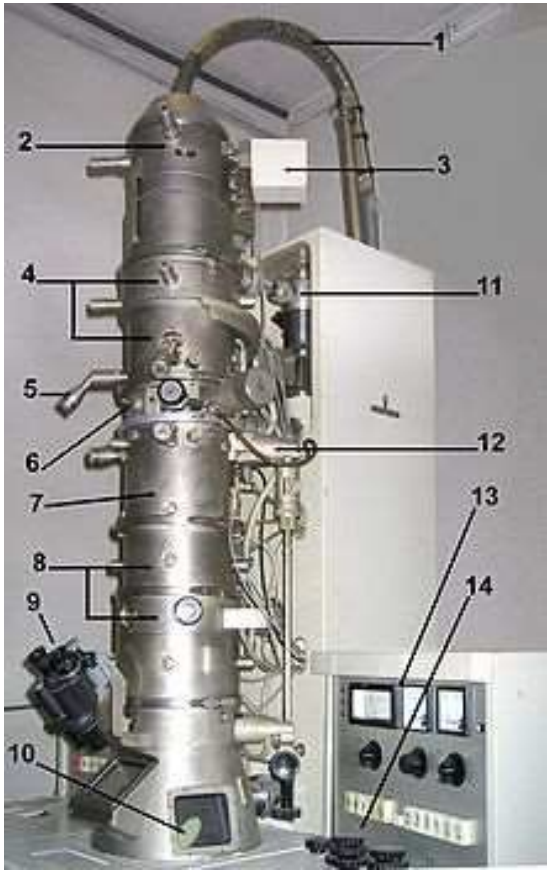



# Five Microscopes
to fit the scale of things



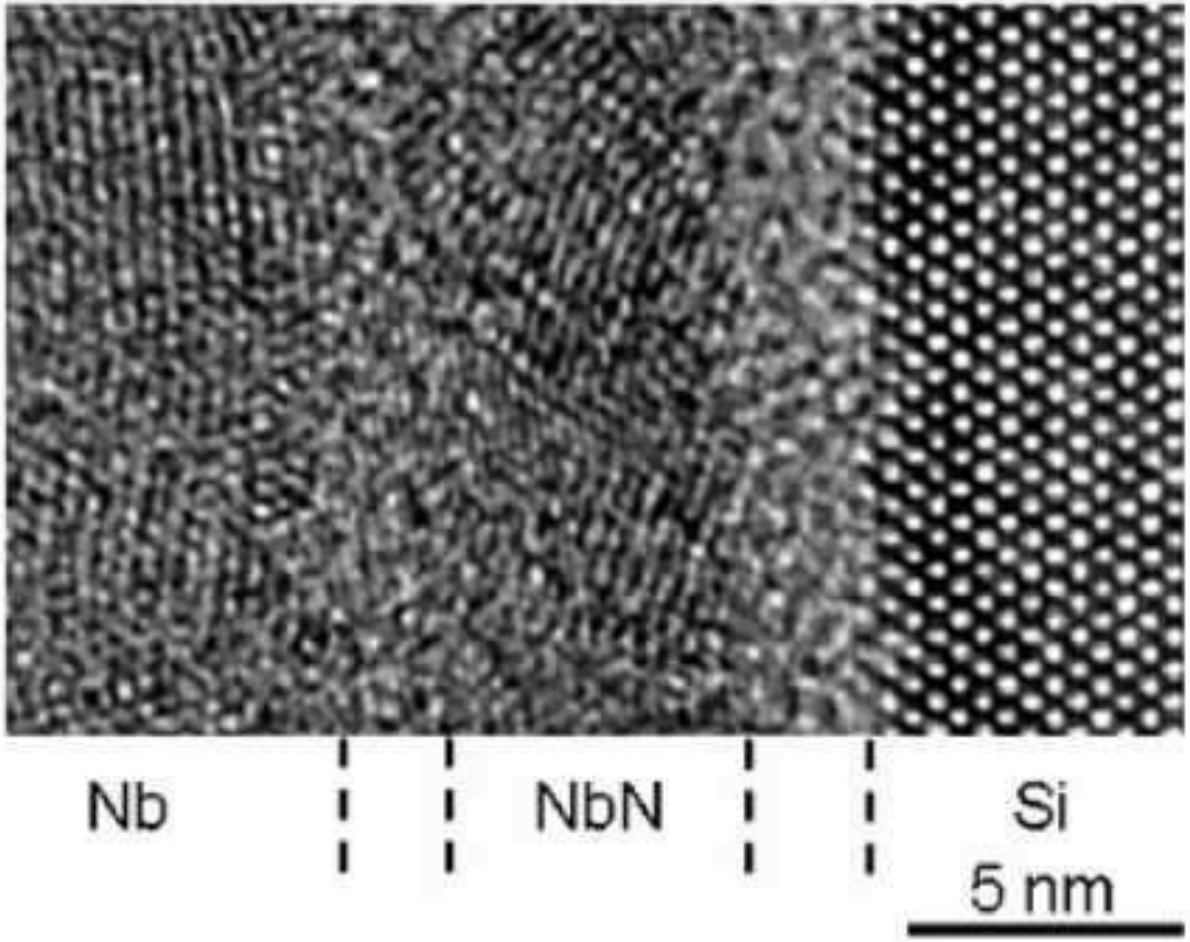

**Scanning Electron (SEM)**




# Transmission Electron Microscope

With each instrument, I'll try to communicate:

- What it does.
- How it works, on a high level.
- Where it's used.
- What subjects can be taught with it.
- What skills your students can learn from it. *(this is subjective)*

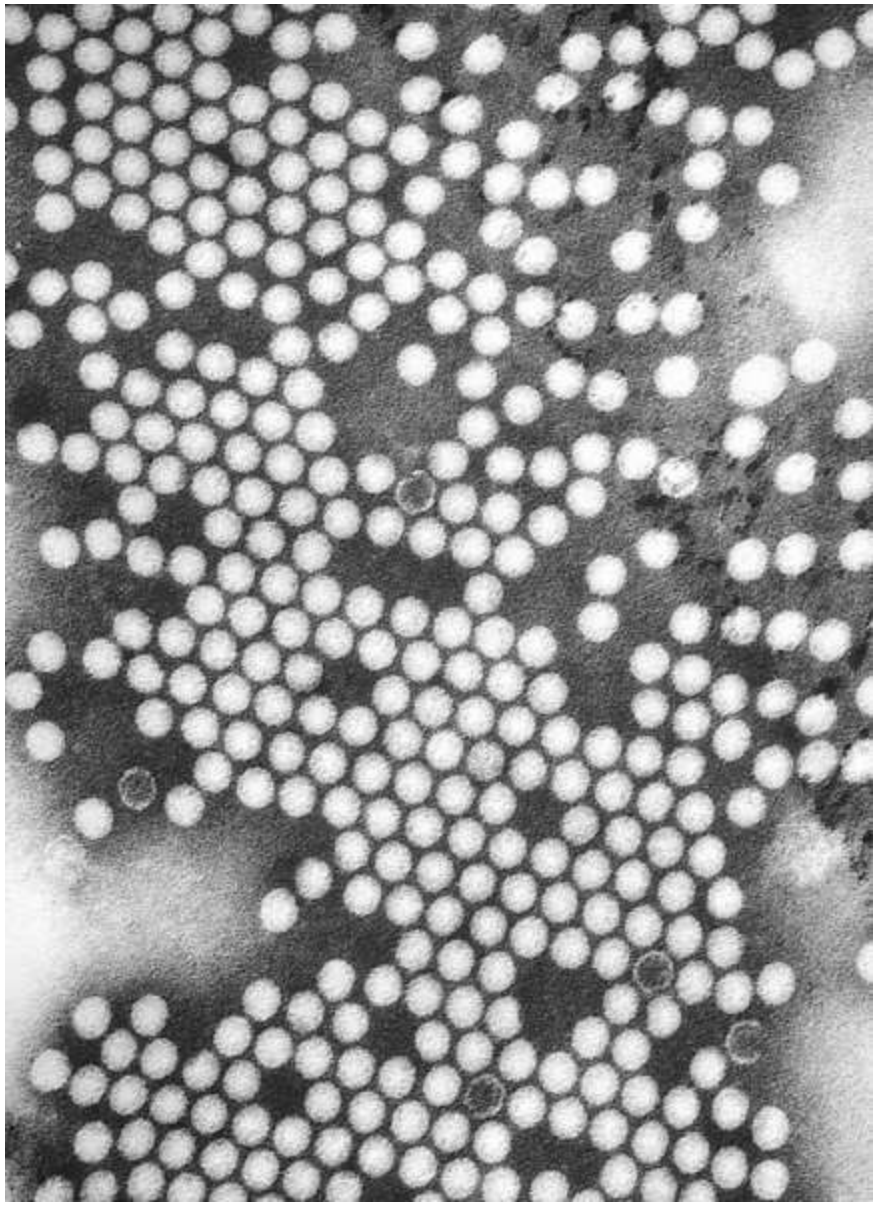



Layer structure on a silicon substrate:

(Photo by: Siegel/Gerthsen).

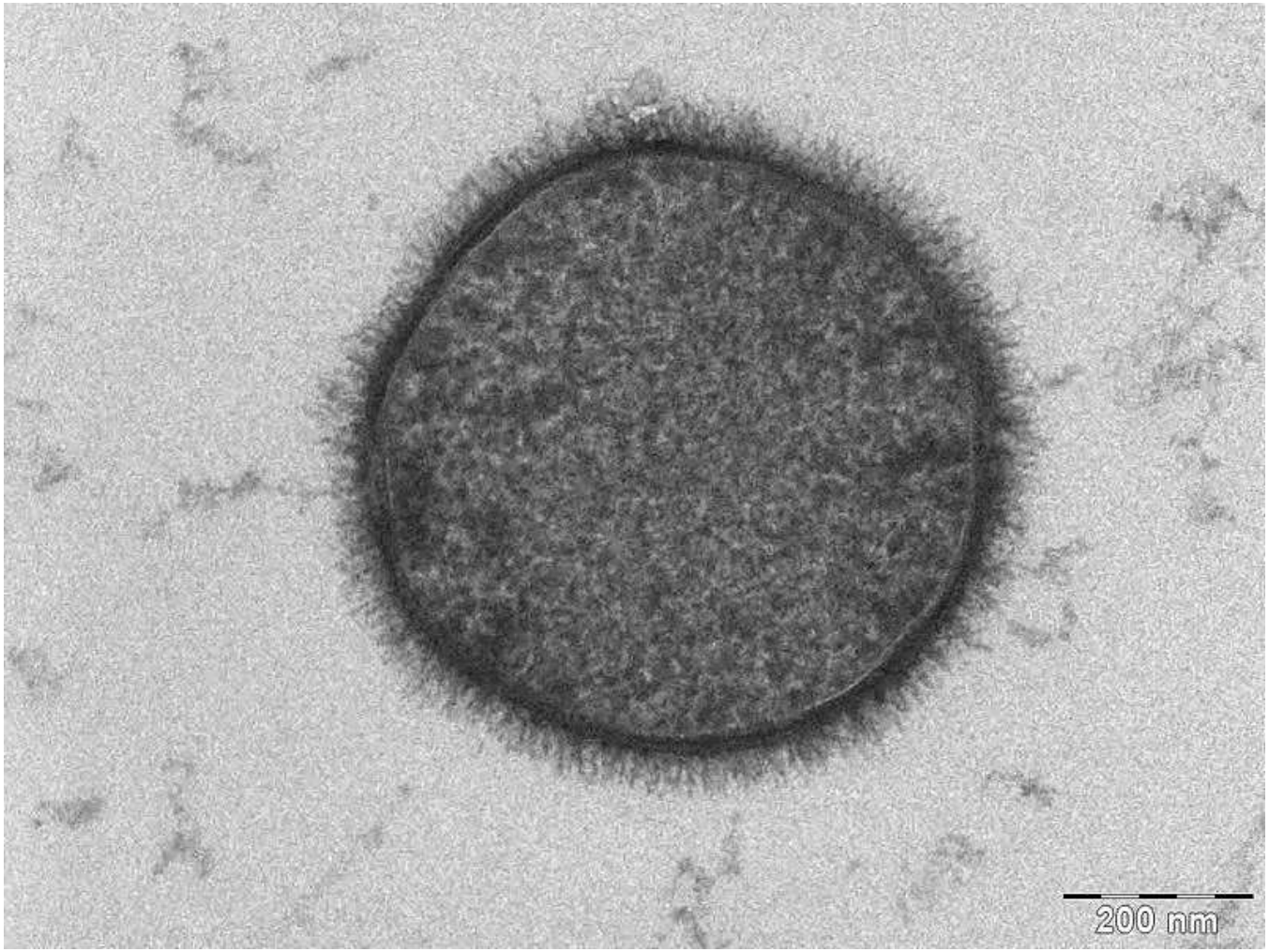
http://www.kit.edu/visit/1839_156.php

# TEM – What it does?

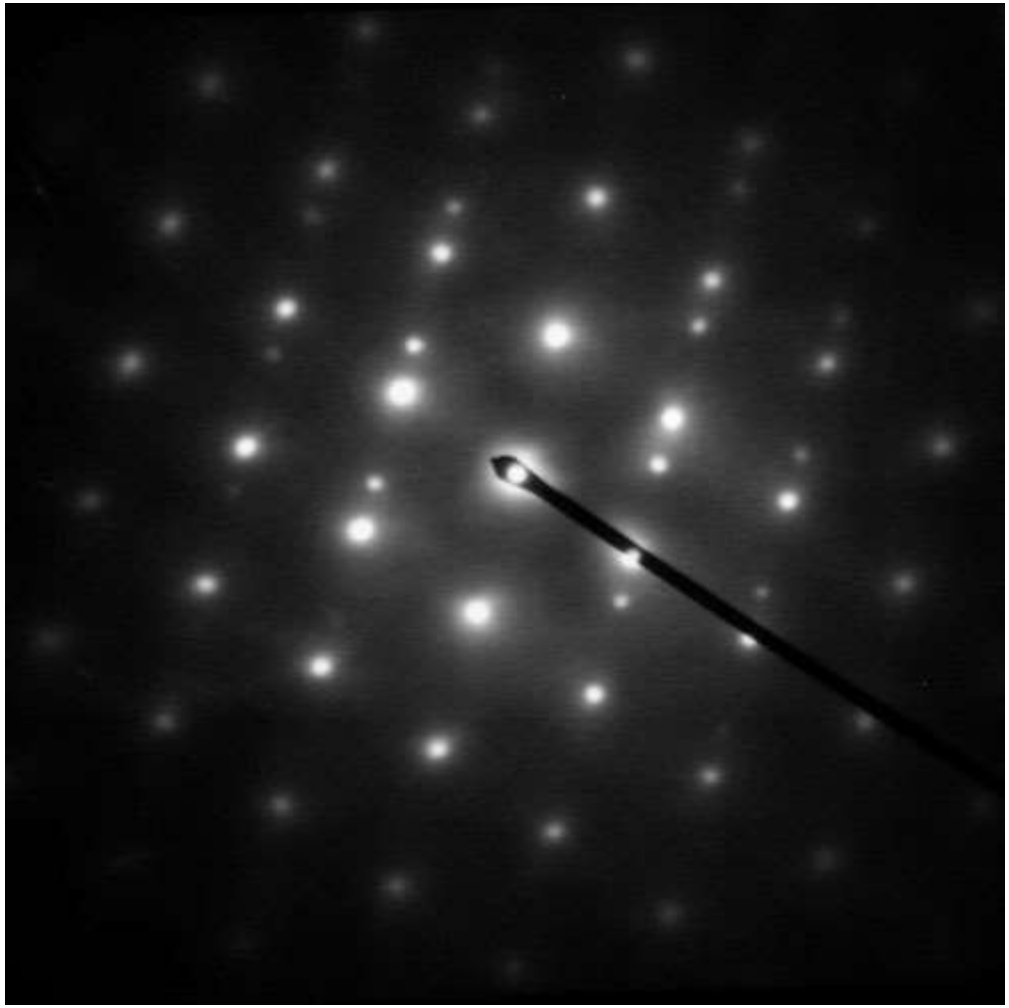


http://en.wikipedia.org/wiki/Transmission_electron_microscopy#cite_note-1

A TEM image of the polio virus.
The polio virus is 30 nm in size.

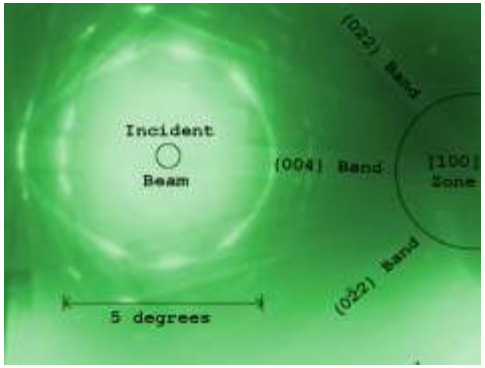



A section of a cell of *Bacillus subtilis*, taken with a Tecnai T-12 TEM. The scale bar is 200 nm.



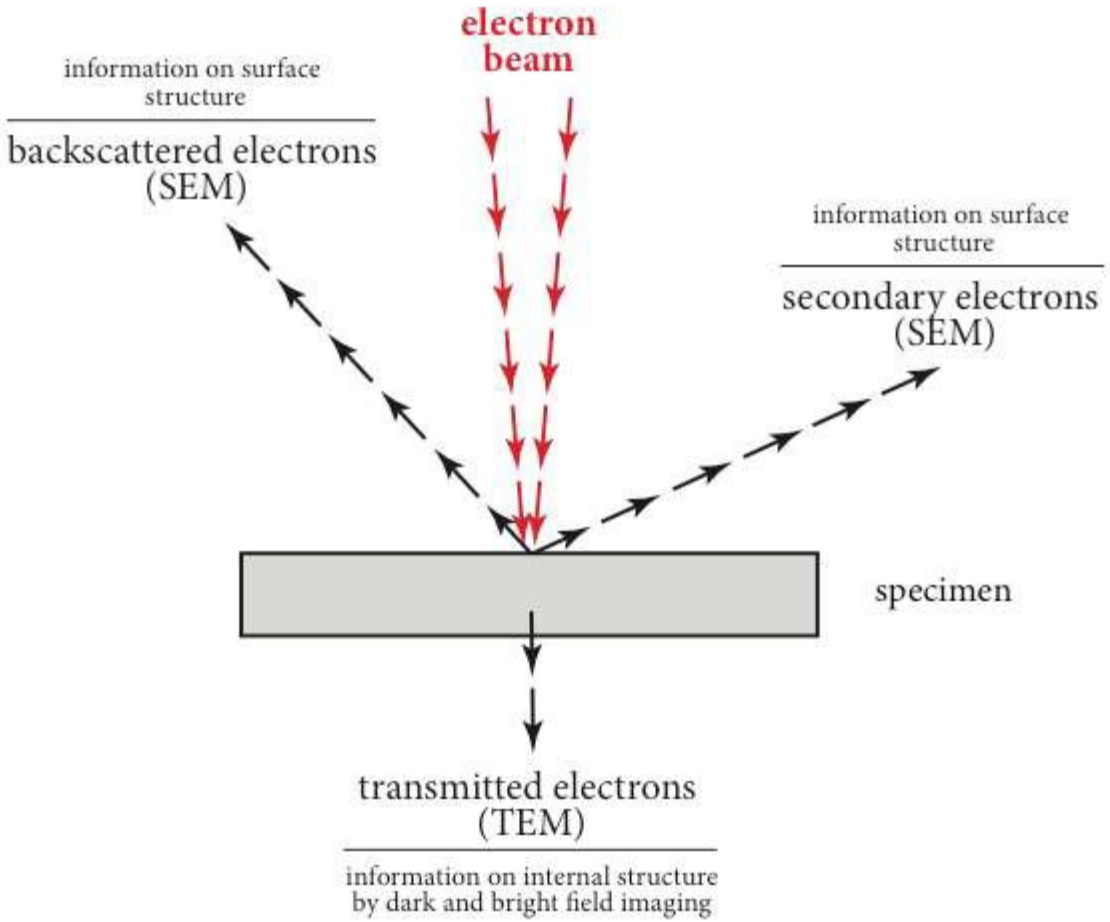
Crystalline diffraction pattern from a twinned grain of FCC Austenitic steel

Transmission electron micrograph of dislocations in steel

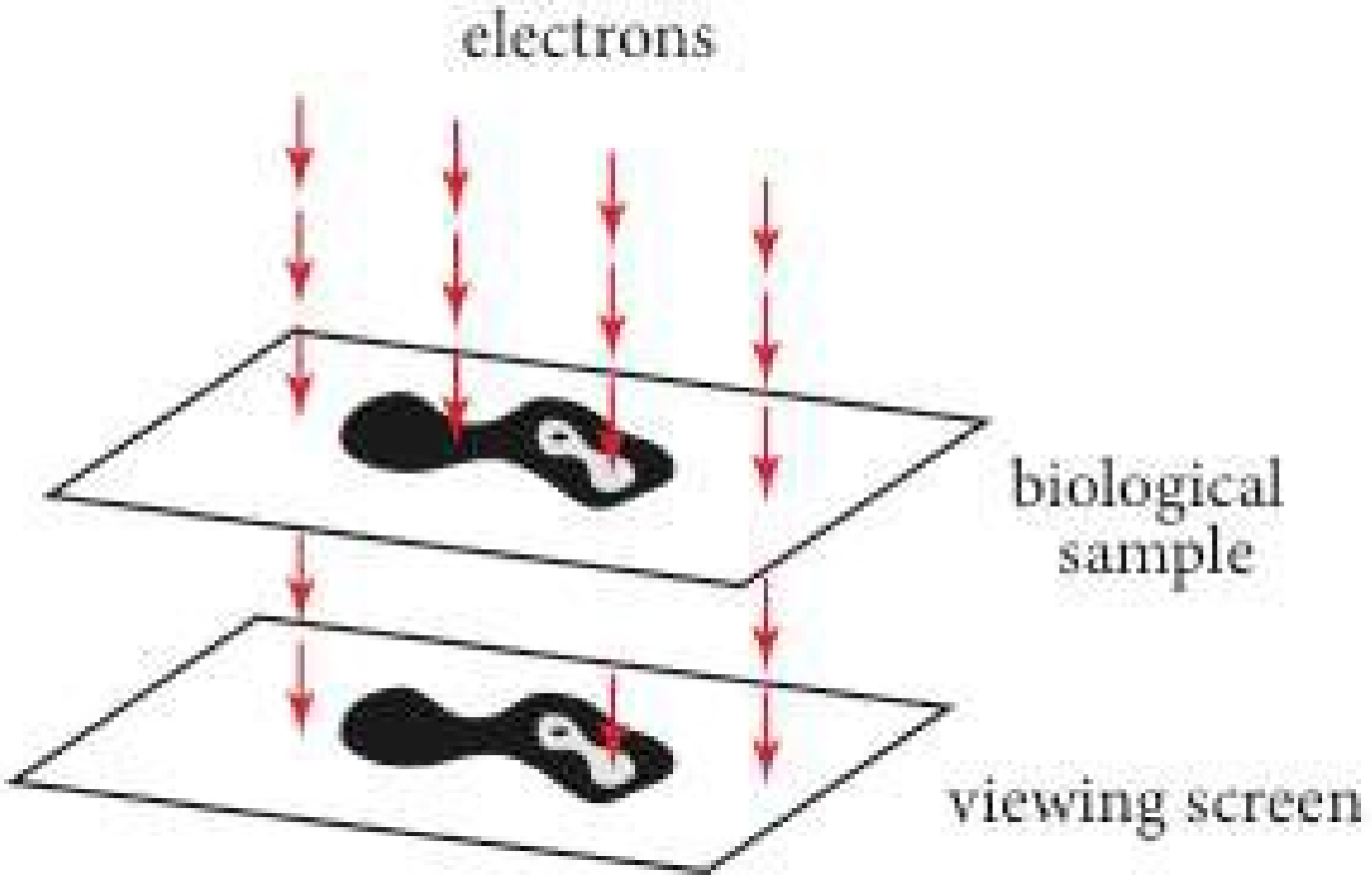



Convergent-beam Kikuchi lines from silicon, near the [100] zone axis

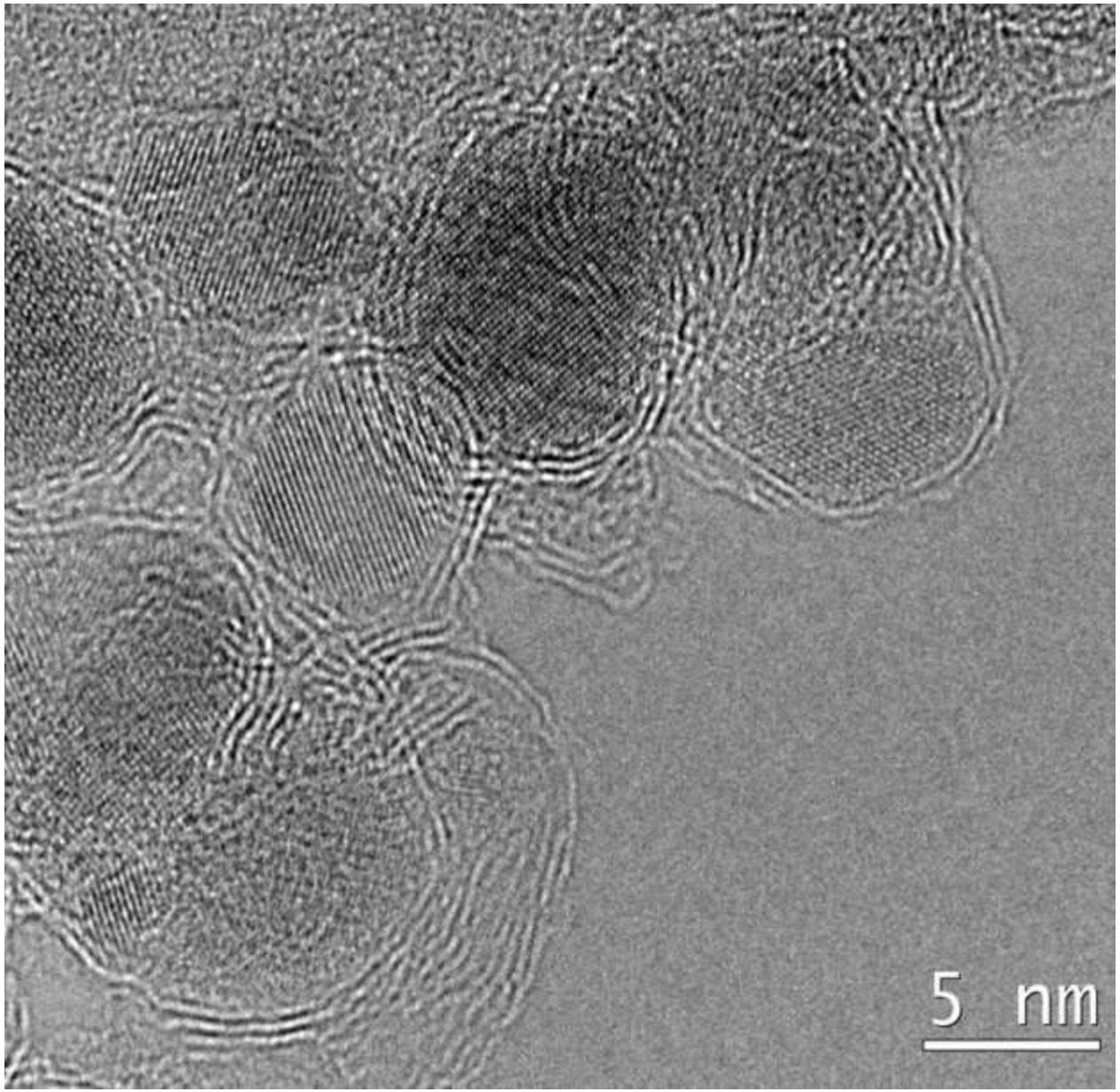
# TEM – How does it work?



# TEM – How does it work?




TEM

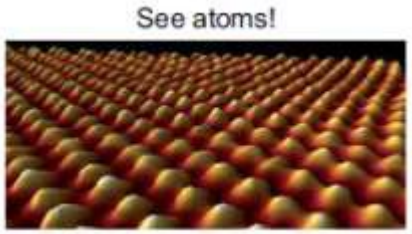


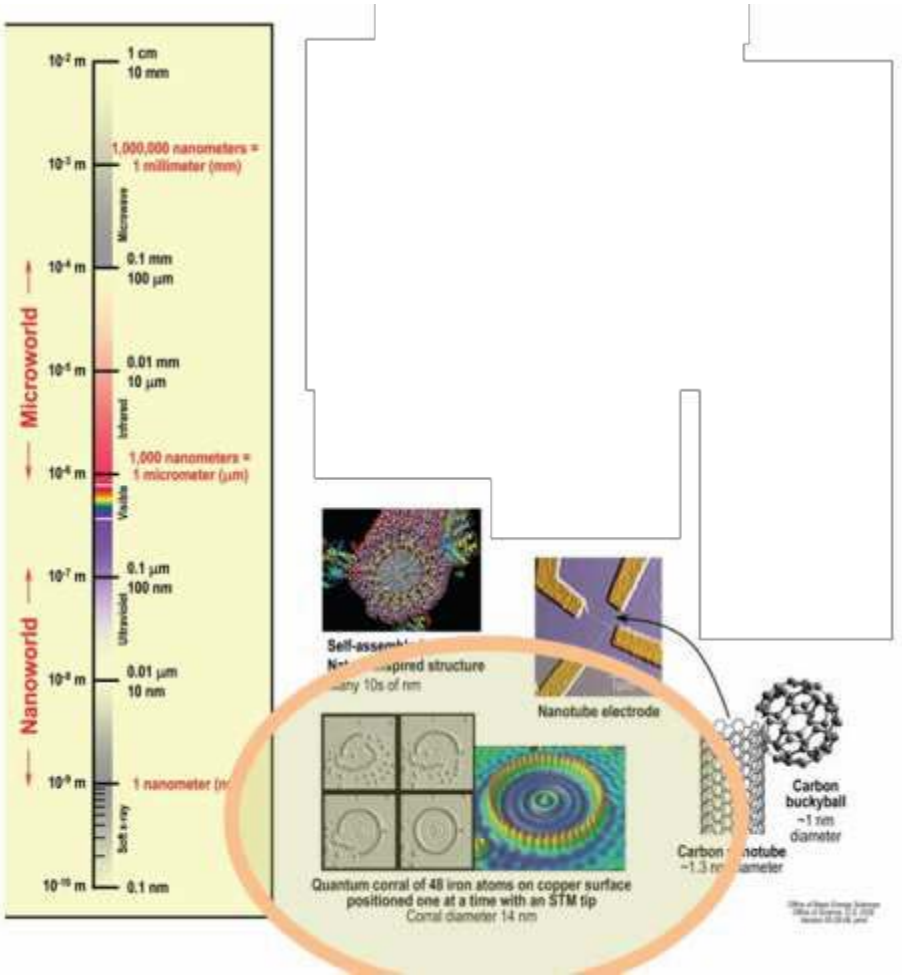

**HRTEM image of a Fe/LiF/C anode for lithium ion batteries**

*R. Prakash and C. Kübel et al., J. Power Sources, 2011, 196, 5936-5944.*

# SCANNING TUNNELING MICROSCOPE

- What it does:
  - Measures and creates a visual representation of very smooth, atomic level, surfaces. Image atoms.



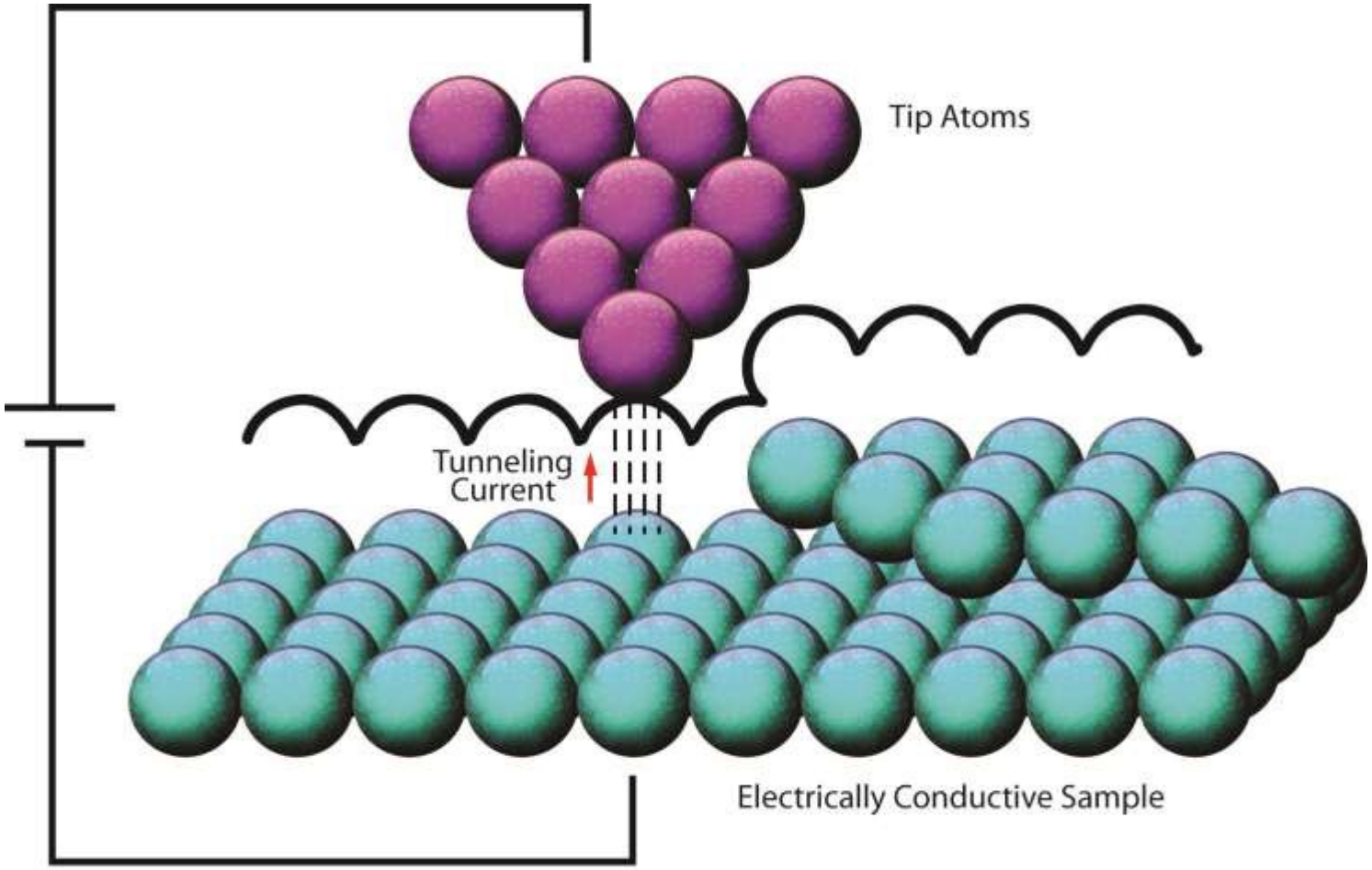




Iconic image of “Nano” from IBM in the 90’s - “Quantum Corral”

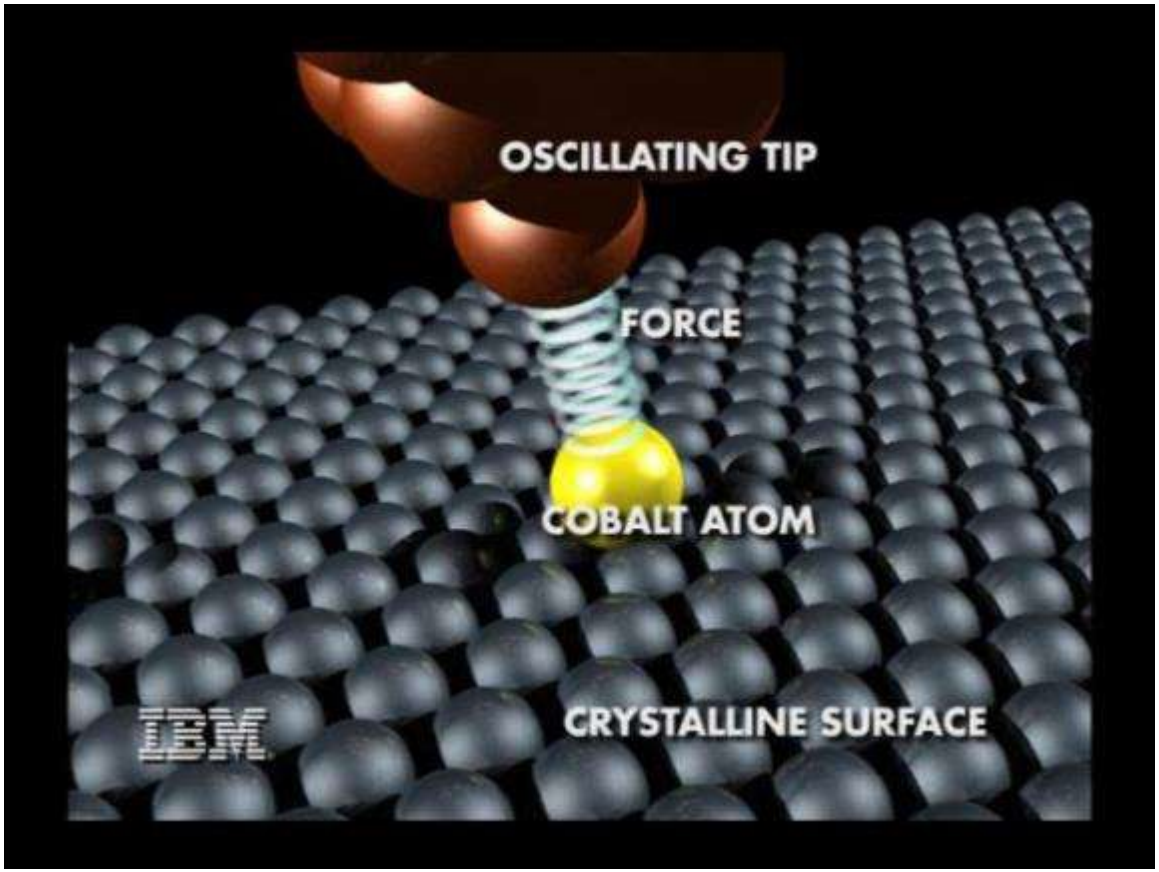
# A Boy and His ATOM – World's Smallest Movie (IBM)

http://www.youtube.com/watch?v=oSCX78-8-q0

# Quantum Tunneling



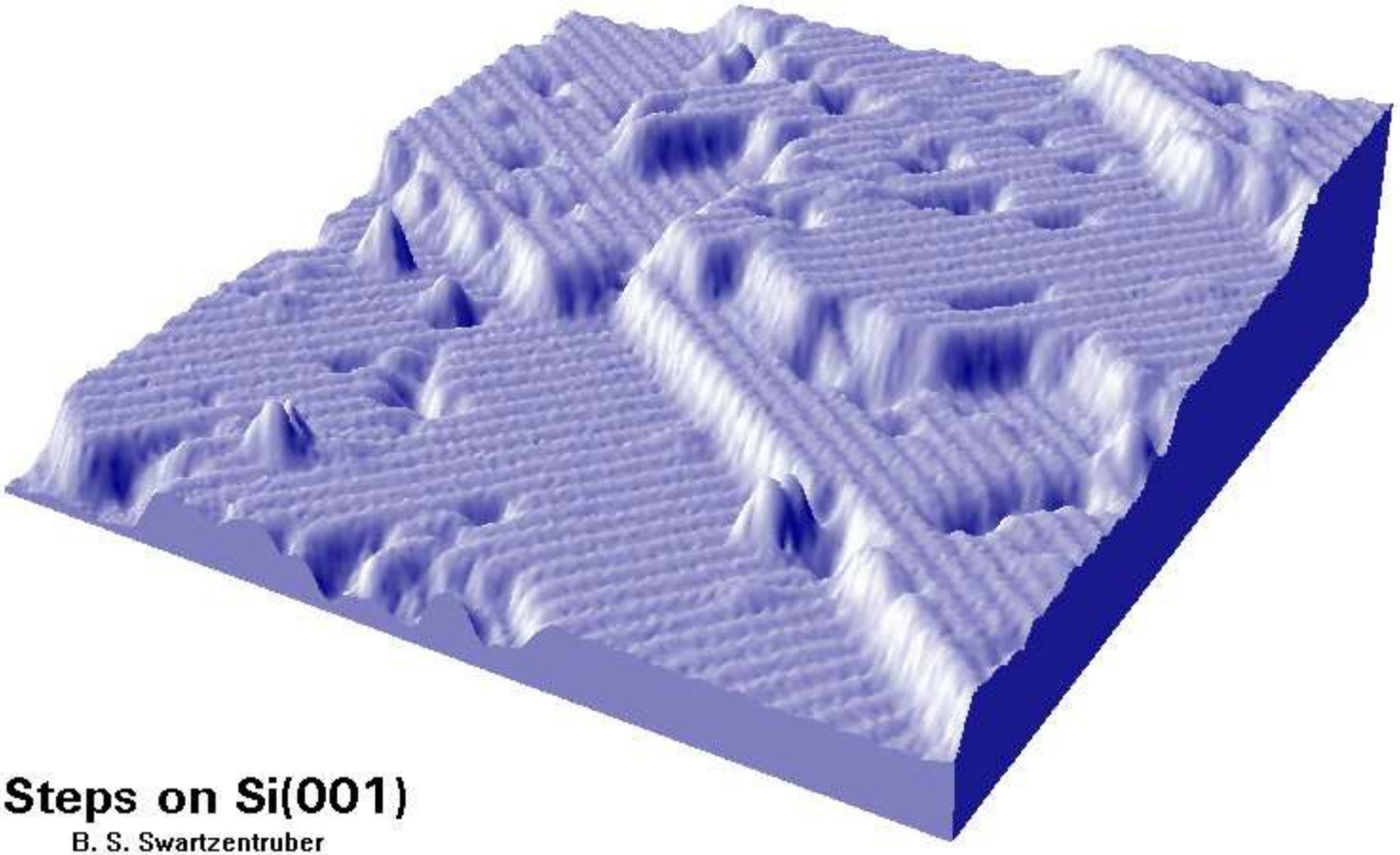
**Artist's impression of the IBM microscope tip**




http://physicsworld.com/cws/article/news/2008/feb/27/feeling-the-force-on-a-single-atom

# Where it's used:

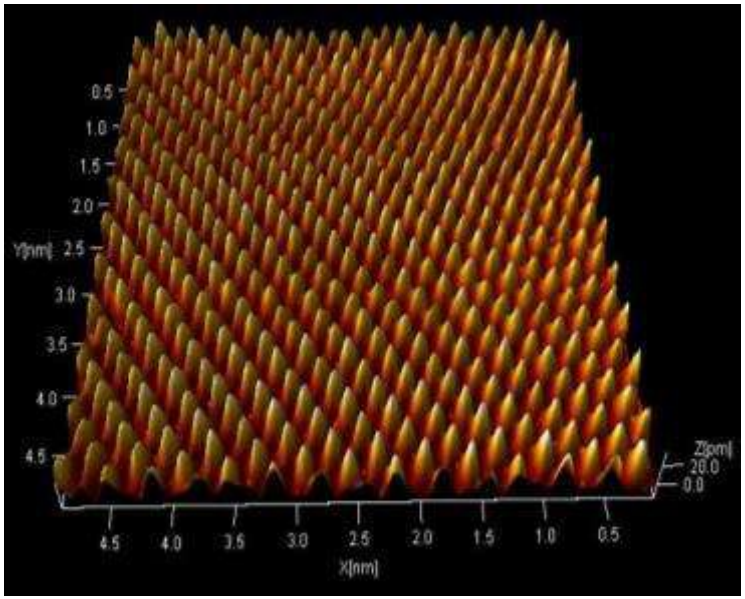
- Advanced Research Labs
- *Teaching and Outreach*
- *Any other industrial uses, audience?*



**Steps on Si(001)**

B. S. Swartzentruber

# Imaging atoms and beyond….




- What subjects can be taught with it.
  - See ATOMS!
  - Physics
- What skills your students can learn from it. *(this is subjective)*
  - *Conceptualization*
  - *Understanding data, and how it was collected*
  - *Operating delicate equipment*
  - *Not quite a resume skill yet.*

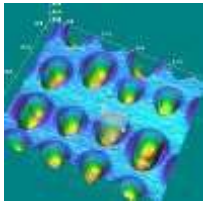
# TEST… Match the image group with the Scope

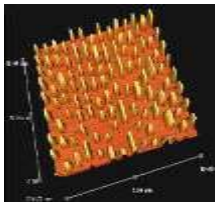
*3D Optical Microscope*

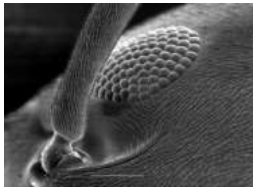
*SEM*

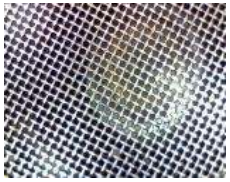
*AFM*

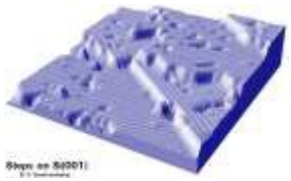
*STM*











# Is it Practical?

Classroom Integration – Square Peg, Round Hole?

**Five Microscopes**

to fit the scale of things

**3D Optical**

Wavelength of Light

**Scanning Electron (SEM)**

Wavelength of Electron

**Atomic Force (AFM)**

Atomic Force

**Transmission Electron (TEM)**

Electron interaction through a material

**Scanning Tunneling (STM)**

Quantum Force


your clean room
isn't
like


**Making microprocessors is a tricky business.**
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# Practical Considerations

When considering investing in instrumentation…

- **Fast – to use – classrooms have a boxed time**
  - A 20 min “get ready” time per instrument is not realistic

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- **Easy-to-use "real" scientific instrument**
  - Not a model; not 'dummed down' equipment; a real instrument made intuitive; think "iPad"
  - Capable of the same type of experiments in research institutions and industry; measures in the same way

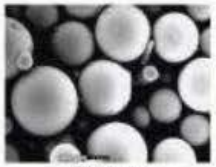
# Is it Practical?
# That's not the question…
# Is it do-able?
# Answer for yourself…

# The Scale of Things – Nanometers and More

## Things Natural

Dust mite
200 μm

Ant
~ 5 mm

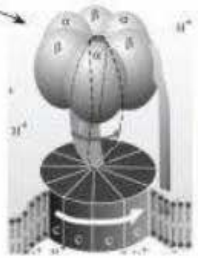


Fly ash
~ 10-20 μm

Human hair
~ 60-120 μm wide

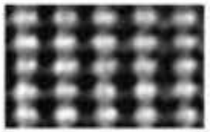
Red blood cells
(~7-8 μm)

~10 nm diameter

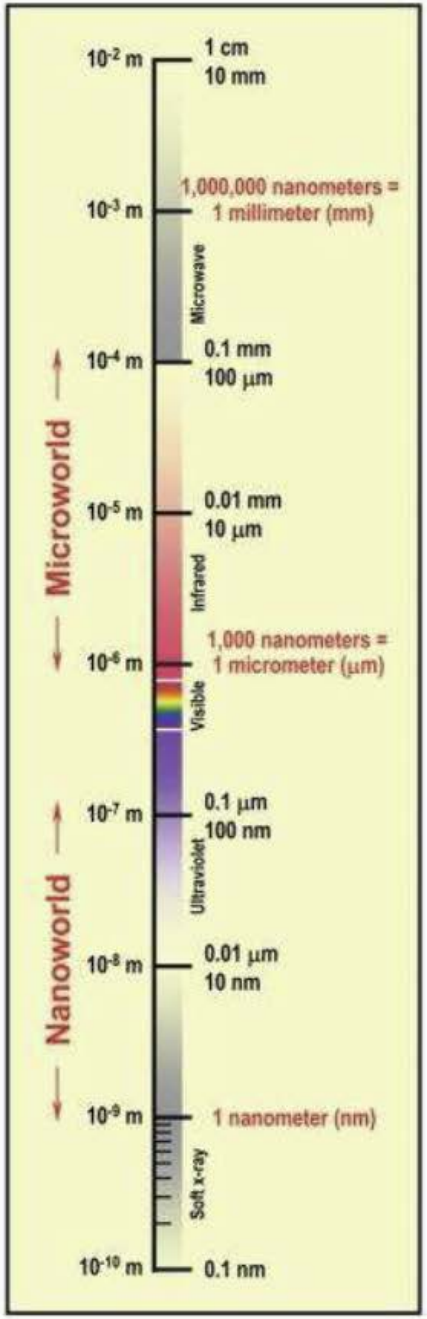


ATP synthase

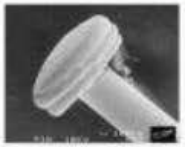
DNA
~2-1/2 nm diameter



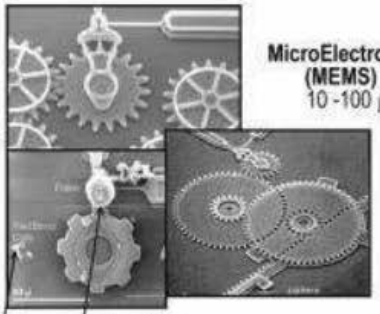
Atoms of silicon
spacing 0.078 nm




## Things Manmade



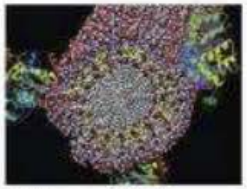
Head of a pin
1-2 mm



MicroElectroMechanical (MEMS) devices
10 -100 μm wide

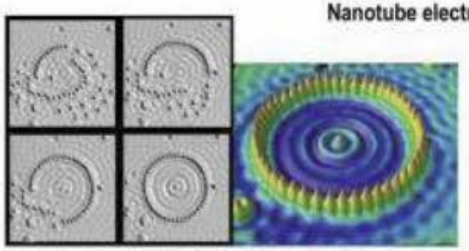
Pollen grain
Red blood cells

Zone plate x-ray "lens"
Outer ring spacing ~35 nm



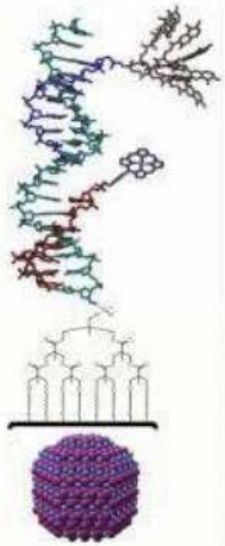
Self-assembled,
Nature-inspired structure
Many 10s of nm


Nanotube electrode

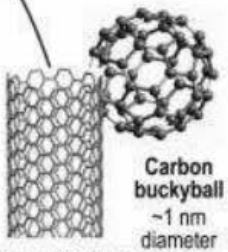


Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip
Corral diameter 14 nm

### The Challenge



*Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.*



Carbon buckyball
~1 nm diameter

Carbon nanotube
~1.3 nm diameter

Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-25-06, pmd

# Questions?

Please type all questions into the Chat Box

# Webinar Recordings

To access this recording, slides, and handout visit

nano4me.org/webinars.php

# Thank You!

Thank you for attending the
NACK Network webinar

**Fundamentals of Metrology and Characterization for Nanotechnology**